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RADONE:
A Computer Code for Simulating Fast-Transient, One-Dimensional Hydrodynamic Conditions and Two-Layer Radionuclide Concentrations Including the Effect of Bed-Deposition in Controlled Rivers and Tidal Estuaries

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Energy Division

RADONE: A COMPUTER CODE FOR SIMULATING FAST-TRANSIENT, ONE-DIMENSIONAL HYDRODYNAMIC CONDITIONS AND TWO-LAYER RADIONUCLIDE CONCENTRATIONS INCLUDING THE EFFECT OF BED-DEPOSITION IN CONTROLLED RIVERS AND TIDAL ESTUARIES

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SUMMARY

This report presents the RADONE computer code of the transient, one-dimensional, two-layer hydrodynamic and radionuclide transport model in two major parts: (1) the summaries of the mathematical formulation of the governing system of discrete-element equations and the computational procedure of its solution algorithm, including samples of the computer simulation results of its applications to the site-specific problems of the Hudson River estuary and (2) the complete users manual with detailed instructions for its implementation.

The structure of the RADONE computer code is based on the application of the one-dimensional form of the "discrete-element method" (DEM), which represents a locally conservative discretization technique, to the development of an advanced radionuclide transport model for simulating fast-transient (tidal-transient), one-dimensional water concentrations of the radionuclide in the water layer and the bottom concentrations of the radionuclide in the bottom layer of the main flow channel of a controlled river or a tidal estuary, with temporally and longitudinally varying (or uniform) hydrodynamic conditions, during and after controlled or accidental radionuclide release scenarios into the water body.

The mathematical model includes a hydrodynamic submodel that can accurately predict fast-transient, one-dimensional water surface elevation and channel flow rate conditions along the curvilinear longitudinal *x*-axis of the main flow channel of a controlled river or a tidal estuary. The RADONE computer code includes a user-specified option either for utilizing the hydrodynamic submodel for simulating the flow conditions or for deactivating the hydrodynamic submodel, and for utilizing specified input data for the flow conditions, during the simulations of the radionuclide concentration conditions in a controlled river or a tidal estuary.

The mathematical model approximately but realistically considers the vertical and lateral variations of the channel flow velocity and the water concentration of the radionuclide in the water layer in the development of the explicit forms for the convection-defect radionuclide transport rate and the eddy-turbulent radionuclide transport rate in the formulation of the nonconvective radionuclide transport rate along the curvilinear longitudinal *x*-axis of the main flow channel. Hence, it eliminates the need for specifying site-specific values for unrealistic and questionable "dispersion coefficients," which are generally different for different controlled rivers and for different tidal estuaries.

The mathematical model approximately but realistically incorporates the radiological bottom uptake and release effects, by considering simultaneously local conservation principles for the water concentration of the radionuclide in the water layer and the bottom concentration of the radionuclide in the bottom layer, and by formulating approximate but physically realistic bottom radionuclide transport conditions, in terms of bottom-mixing radionuclide transport, bottom-settling (deposition) radionuclide transport, and bottom-resuspension (scouring) radionuclide transport, between the water layer and the bottom layer, depending on the local, site-specific flow conditions in the main flow channel.

RADONE computer code is specifically designed to enable the user to implement the transient, one-dimensional, two-layer radionuclide transport model for studying the development of the contaminated zones as parts of the longitudinal length of the main flow channel, during and after an actual controlled or accidental radiological release scenario in an actual controlled river or a tidal estuary. Hence, the input data formats of the RADONE computer code have all the necessary capabilities for incorporating wide ranges of site-specific information, including (a) information with wide ranges of spatial resolution for the geometrical characteristics of the main flow channel; (b) information with wide ranges of temporal and/or spatial resolution for the controlled and/or tidal flow conditions and radionuclide concentration conditions,

associated with the end conditions, rainfall and drainage conditions, stream and tributary conditions, and groundwater seepage conditions in the geographic (climatological) region; and (c) information with wide ranges of temporal and spatial resolution for the plant operational and radionuclide release conditions, along the curvilinear longitudinal x-axis of a controlled river or a tidal estuary.

Preliminary applications of the RADONE computer code to study the consequences of hypothetical accidental radiological prompt-release scenarios in the Hudson River estuary established that the computer simulation results for the radionuclide concentration conditions, obtained by the fast-transient, one-dimensional, two-layer radionuclide transport model, which considers simultaneously the water concentration of the radionuclide in the water layer and the bottom concentration of the radionuclide in the bottom layer by incorporating approximately but realistically all the important bottom radionuclide transport effects between the water layer and the bottom layer, could be significantly different from the computer simulation results for the radionuclide concentration conditions, obtained by a relatively simple, conventional radionuclide transport model, which considers the radionuclide as a passive contaminant only in the water layer, based on simple formulations of only the radiological bottom uptake effects, in predicting the development of the contaminated zones during and after an accidental radiological release, in a controlled-flow river or a tidal estuary.

ABSTRACT

RADONE is a computer code for predicting the transient, one-dimensional transport of radionuclides in receiving water bodies. The model formulation considers the one-dimensional (cross-sectionally averaged) conservation of mass and momentum equations and the two coupled, depth-averaged radionuclide transport equations for the water layer and the bottom sediment layer. The coupling conditions incorporate bottom deposition and resuspension effects. The computer code uses a discrete-element method that offers variable river cross-section spacing, accurate representation of cross-sectional geometry, and numerical accuracy. A sample application is provided for the problem of hypothetical accidental releases and actual routine releases of radionuclides to the Hudson River.

1. INTRODUCTION

1.1 GENERAL CONSIDERATIONS

One of the critical public concerns about the operation of a nuclear electric-power generating station, or any other nuclear facility, along a controlled river or a tidal estuary, is the short-term and long-term health hazards of the potential accidental radiological releases into the receiving water body. The public concern about the potential accidental radiological releases varies from (a) the occurrence of relatively high probability, low-level radiological releases into the cooling water system of the nuclear plant, which ultimately are discharged at relatively low rates of release, into the receiving water body, to (b) the occurrence of the extremely low-probability catastrophic event, which may result in massive radiological releases into the water body during and after a core melt accident. Hence, the U.S. Nuclear Regulatory Commission (NRC) has been supporting in-house and external research programs for the development of scientifically sound and publicly acceptable methodologies for studying the outcomes of various classes of accidental radiological releases from nuclear power plants and other nuclear facilities in order to accurately estimate the short-term and long-term health hazards and the radiological impact of these radiological releases on the site-specific ecologies of the water bodies, including lakes, reservoirs, rivers, estuaries, and coastal regions. The current state of the art in mathematical modeling of radionuclide transport in the receiving water bodies and other methodologies that can be used for studying the consequences of accidental radiological releases from nuclear power plants and other nuclear facilities are presented and reviewed in various scientific documents prepared for NRC, including NUREG-75/014 (WASH-1400) (1975), Regulatory Guide 1.113, Rev. 1 (1977), and NUREG/CR-2974 (ORNL/TDMC-2) [White and Eckerman (1982)].

This report presents a fast-transient (tidal-transient), one-dimensional, two-layer radionuclide transport model (and its associated RADONE computer code) that was completed as a part of the Radiological Program of the research project entitled "Development of a Unified Transport Approach (UTA) for the Assessment of Power-Plant Impact" [Eraslan et al. (1977), Eraslan and Witten (1984)], sponsored by the Division of Safeguards, Fuel Cycle, and Environmental Research of NRC.

The objective of the UTA project is the development of fast-transient, one-, two-, and three-dimensional mathematical transport models and their associated general-usage computer codes, which can be used to predict hydrodynamic, thermal, radiological, chemical, and biological (entrainment and impingement) impacts of power plant operations on rivers, estuaries, lakes, and coastal regions. The UTA concept utilizes all the common features of the transport of water mass, momentum, thermal energy, chemical constituent mass, sediment, radionuclide activity, and aquatic biota population in that it considers (1) common formulations of the mathematical transport models based on state-of-the-art, discrete-element methods; (2) common structures of the computer codes based on optimized, consistent, and stable numerical solution algorithms; (3) common and/or identical input data formats for all common, site-specific environmental and plant operational conditions; and (4) common formats for the presentation of results based on advanced computer graphics programs. The UTA models eliminate all duplicative effort in their development and in their applications to site-specific problems; hence, they can save substantial time, manpower, and computer cost in completing the required studies for the assessment of the total impact (hydrodynamic, thermal, chemical, radiological, and biological) of power plant operations on the aquatic ecology of a water body.

According to the fundamental UTA concept, the mathematical formulation of the fast-transient (tidal-transient), one-dimensional, two-layer radionuclide transport model is based on the unifying mathematical formulation of transport phenomena used in the development of all one-dimensional, discrete-element transport models of the UTA project [e.g., Eraslan et al. (1976), Eraslan and Witten (1984)]. Furthermore, again according to the fundamental UTA concept, the computational structure of the RADONE computer code is based on the common unifying computational structure used in the development of all associated computer codes of the fast-transient, one-dimensional transport models for controlled rivers and tidal estuaries.

There are four computer codes associated with the nine one-dimensional, discrete-element transport models developed in the four topical programs of the UTA project [Eraslan et al. (1976), Eraslan and Witten (1984)]:

1. ESTONE, for the Thermal Program,
2. CHMONE, for the Chemical Program,
3. SEDONE, for the Sediment Program, and
4. RADONE, for the Radiological Program.

According to the fundamental UTA concept, the mathematical formulation of the fast-transient (tidal-transient), one-dimensional, discrete-element transport model for predicting hydrodynamic, thermal, and salinity conditions in controlled rivers and tidal estuaries, which is the foundation of the computational algorithm of the ESTONE computer code [Eraslan (1983)], also serves as the common unifying mathematical formulation of all four one-dimensional, discrete-element transport models of the UTA project [Eraslan et al. (1976), Eraslan and Witten (1984)].

1.2 CONSIDERATIONS OF TRANSIENT, ONE-DIMENSIONAL, TWO-LAYER RADIONUCLIDE CONCENTRATION CONDITIONS

The transient, multidimensional transport of a radionuclide in an aquatic flow region is controlled by a large number of physical, physicochemical and biochemical phenomena, which depends on the site-specific characteristics of the general ecology of the water body. Therefore, in order to develop a truly advanced state-of-the-art, fast-transient, multidimensional radionuclide transport model, with general site-specific application capabilities, it would be necessary to consider detailed and accurate information either in the form of reliable and accurate site-specific field-measured data and/or in the form of computer simulation results obtained by site-specific applications of other advanced state-of-the-art mathematical models, about the following, but not necessarily limited to, physical, physicochemical, and biochemical conditions in each water body.

1. *Hydrodynamic Conditions:* Accurate information about the hydrodynamic conditions must be considered as first priority information, because the flow conditions in the water body are the most important physical phenomena of the overall transport conditions of the radionuclide in a river or an estuary. The hydrodynamic conditions control the detailed transport mechanisms, consisting of (a) the convective transport, (b) the eddy-turbulent transport (and molecular transport), and (c) the dispersive transport (i.e., in the general sense, resulting from spatial variations in spatially averaged approximate formulations), which control the temporal and spatial variations of the radionuclide concentration conditions in all possible different states, including (a) the dissolved state, (b) the adsorbed states on different, multiple classes (i.e., based on size, mass, and chemical composition) of sediment, and (c) the more complex sorbed (i.e., adsorbed and/or absorbed) states on/in different classes of organic matter in the aquatic region of a river or an estuary.

2. *Sediment Conditions:* Accurate information about the sediment conditions must be considered as second priority information, since the majority of the important radionuclides, which may be introduced into the water bodies as consequences of accidental radiological releases, get adsorbed on most classes of sediment that naturally exist in suspended and/or deposited forms in a river or an estuary. Since, in general, for a particular radionuclide, different levels of adsorption preference exist for different classes of sediment, depending strongly on the size and chemical composition characteristics of different classes of sediment, detailed and accurate information about the temporal and spatial variations of all important sediment classes may be required for considering the transport of adsorbed states of the radionuclide on different classes of sediment. Therefore, detailed and accurate information about the transport phenomena, associated with different, multiple classes of sediment, including (a) the longitudinal sediment transport phenomena, with water flow in the main flow channel, associated with suspended, multiple classes of sediment and (b) the vertical sediment transport phenomena, associated with settling into the bottom layers (deposition) and resuspension into the flowing water layers (scouring), must be included in the consideration of the transport of the adsorbed states of the radionuclide on different, multiple classes of sediment in a river or an estuary.
3. *Physicochemical Water Quality Conditions:* Additional, accurate information about the physicochemical water quality conditions must also be considered, as second priority information, since, for the majority of the important radionuclides, which may be introduced into the water bodies as consequences of accidental radiological releases, the adsorption (or desorption) characteristics of the radionuclide on different sediment classes (particularly with different chemical compositions) strongly depend on the local site-specific physicochemical water quality conditions. Indeed, the local site-specific water temperature conditions, salinity conditions, and pH conditions can control the partitioning of the radionuclide concentration conditions between the dissolved state and different adsorbed states on different, multiple classes of sediment. Furthermore, the presence of industrial chemicals as additional chemical contaminants, at different concentration levels, can also affect strongly the adsorption (and desorption) characteristics of different radionuclides on different multiple sediment classes that exist in the suspended and/or deposited states in the water body. Therefore, reasonably detailed and reliable information about the temporal and spatial variations of the physicochemical water quality conditions must also be included in the consideration of the transport of the dissolved state of the radionuclide and the adsorbed states of the radionuclide on different, multiple classes of sediment in a river or an estuary.
4. *Organic Water Quality Conditions:* Additional information about the organic water quality conditions must also be considered as second priority information, since, again, for the majority of the important radionuclides, which may be introduced into the water body as consequences of accidental radiological releases, the adsorption (and desorption) characteristics of the radionuclide on different multiple sediment classes may strongly depend on the local site-specific concentrations of the competing organic matter in the water body. Indeed, the presence of certain organic matter, which can exist in adsorbed states on different multiple sediment classes and which, in turn, can contain the radionuclide in sorbed (adsorbed and/or sorbed) state on/in the particles of the organic matter, may be a significant factor in controlling the concentrations of the different states of the radionuclide in the water body. Therefore, reasonably detailed and accurate information about the temporal and spatial variations of the organic water quality conditions may be required for the consideration of the transport of the dissolved state of the radionuclide, the adsorbed state of the radionuclide on different multiple classes of sediment, and the sorbed (adsorbed and/or absorbed) state of the radionuclide on/in different organic matter in a river or an estuary.

Hence, the development of a truly advanced state-of-the-art, fast-transient, multidimensional radionuclide transport model, which can accurately consider all of the above-stated important physical, physicochemical, and biochemical conditions in the aquatic flow region of a river or an estuary, would require an extensive mathematical model development effort. Various preliminary mathematical models for considering transient, longitudinally one-dimensional and vertically multiple-layer transport of multiple sediment classes and radionuclides in the dissolved state and in the adsorbed states on multiple sediment classes, with or without the hydrodynamic submodels for generating the flow conditions, have already been developed for controlled rivers and tidal estuaries [e.g., Onishi (1980a, 1980b), Eraslan (1983)]. Furthermore, the set of transient one-dimensional, multilayer mathematical transport models, developed in the four topical programs of the UTA project [Eraslan et al. (1976), Eraslan and Witten (1984)], consisting of the associated computer codes as (1) ESTONE [Eraslan (1983)] in the Thermal Program, (2) SEDONE [Hetrick, Eraslan, and Patterson (1979)] in the Sediment Program, (3) CHMONE [Fischer et al. (1984)] in the Chemical Program, and (4) RADONE (this document) in the Radiological Program, can provide all the required modular submodels for developing an advanced state-of-the-art, unified, fast-transient, one-dimensional or multidimensional, multilayer radionuclide transport model, which can realistically and accurately consider all four important, controlling, site-specific, physical, physicochemical, and biochemical phenomena that can control the radionuclide transport conditions in controlled rivers and tidal estuaries. Indeed, at present, the development of an advanced state-of-the-art, unified, fast-transient, one-dimensional or multidimensional, multilayer radionuclide transport model would require only reasonable levels of manpower effort and computer cost, from strictly mathematical modeling considerations. However, it would require substantial levels of manpower effort, equipment cost, and time for developing and completing the well-planned field-measurement programs that can provide the necessary reliable and accurate data about the controlling physical, physicochemical, and biochemical conditions in the aquatic flow region, which would be essential for the validation and, if required, for the calibration of even a fast-transient, one-dimensional, multilayer radionuclide transport model for a river or an estuary. Therefore, from practical considerations, the development of an advanced state-of-the-art, unified, fast-transient, one-dimensional or multidimensional, multilayer radionuclide transport model, which can realistically and accurately consider the important, controlling, site-specific, physical, physicochemical, and biochemical phenomena, would not be cost-effective at this time for investigating the consequences of radiological releases into the controlled rivers and tidal estuaries.

On the other hand, from pragmatic considerations, the critical issue that must be addressed, during and after an accidental radiological release into a river or an estuary, is the availability or nonavailability of the necessary scientific methodologies which can provide, at short notice, the necessary practical forms of approximate (within realistic limits of accuracy) but reliable information about the temporal and spatial variations of the radionuclide concentration conditions that can be used in radiological dose assessment calculations required in health safety analyses. Therefore, it may be more appropriate to determine the practical forms of information that would be required about the temporal and spatial variations of the radionuclide concentration conditions in the water body based on the considerations of the two most important health safety problems that are generally encountered as consequences of an accidental radiological release into a river or an estuary.

1. The first important, short-term health safety problem that must be investigated, at short notice, during and after an accidental radiological release into the water body, requires reliable information about the concentration conditions of the released radionuclide at, and/or in the vicinities of, the locations of the intake structures, along the river or the estuary, which withdraw water from the main flow channel for

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the various water supply systems, including public utility water systems, industrial and power plant cooling water systems, and water treatment facilities. This information, required by the particular short-term health safety problem, is critically important because it is used as the input data for the types of radiological dose assessment calculations associated with first-order, direct pathway analyses.

The first important point that needs to be emphasized is that the investigation of the first important, short-term health safety problem requires only practical, approximate but reliable information about the radionuclide concentration conditions associated with the unit volume of contaminated water mixture that can be withdrawn into the intake of any water supply system along the river or estuary. From pragmatic considerations, the investigation of the first important short-term health safety problem does not require the forms of detailed information about the radionuclide concentration conditions in different individual states, as (a) in the dissolved state in water, (b) in the adsorbed states on different multiple classes of sediment, and (c) in the sorbed (adsorbed and/or absorbed) states on/in different organic matter; but it requires the practical form of relatively simple information about the representative value of the concentration of the radionuclide in the contaminated water mixture, which in a sense represents the overall radionuclide concentration condition, averaged over generally different individual concentrations of all the different states of the radionuclide that can exist in the contaminated water that can flow in the aquatic region and that can be withdrawn directly into the intakes of the water supply systems. Hence, in summary, the first important short-term health safety problem requires information in the relatively simple, one-dimensional form as the value of the "water concentration of the radionuclide in the water layer" that can be transported with the flow conditions along the curvilinear longitudinal axis of the main flow channel of a river or an estuary.

2. The second important, long-term (under certain conditions also short-term) health safety problem that must be investigated, during and after an accidental radiological release into the water body, requires information about the deposition and accumulation conditions of the released radionuclide at the bottom of the main flow channel of the river or estuary. This information required by the particular long-term health safety problem is also critically important because it is used as the input data for the types of radiological dose assessment calculations associated with relatively complex, long-term, food-chain pathway analyses, which must consider bioaccumulation characteristics of the different aquatic species, which may have different habitats in different subregions along the river or estuary.

   The second important point that needs to be emphasized is that the investigation of the second important, long-term health safety problem also requires only practical, approximate but reliable information about the radionuclide concentration conditions associated with the unit volume (or unit surface area) of contaminated bottom matter, including water, settled (deposited) sediment classes, and settled (deposited) organic matter that generally remains at the bottom in different subregions along the river or estuary. Again, from pragmatic considerations, the investigation of the second important, long-term health safety problem does not require the forms of detailed information about the radionuclide concentration conditions in different individual states, as (a) in the dissolved state in water, (b) in the adsorbed states on different multiple classes of sediment, and (c) in the sorbed (adsorbed and/or absorbed) states on/in different organic matter; but it requires the practical form of relatively simple information about the representative value of the concentration of the radionuclide in the contaminated bottom matter, which in a sense represents the overall radionuclide concentration conditions, averaged over generally different, individual concentrations of all different states of the radionuclide that can exist in the contaminated bottom matter that can accumulate at certain

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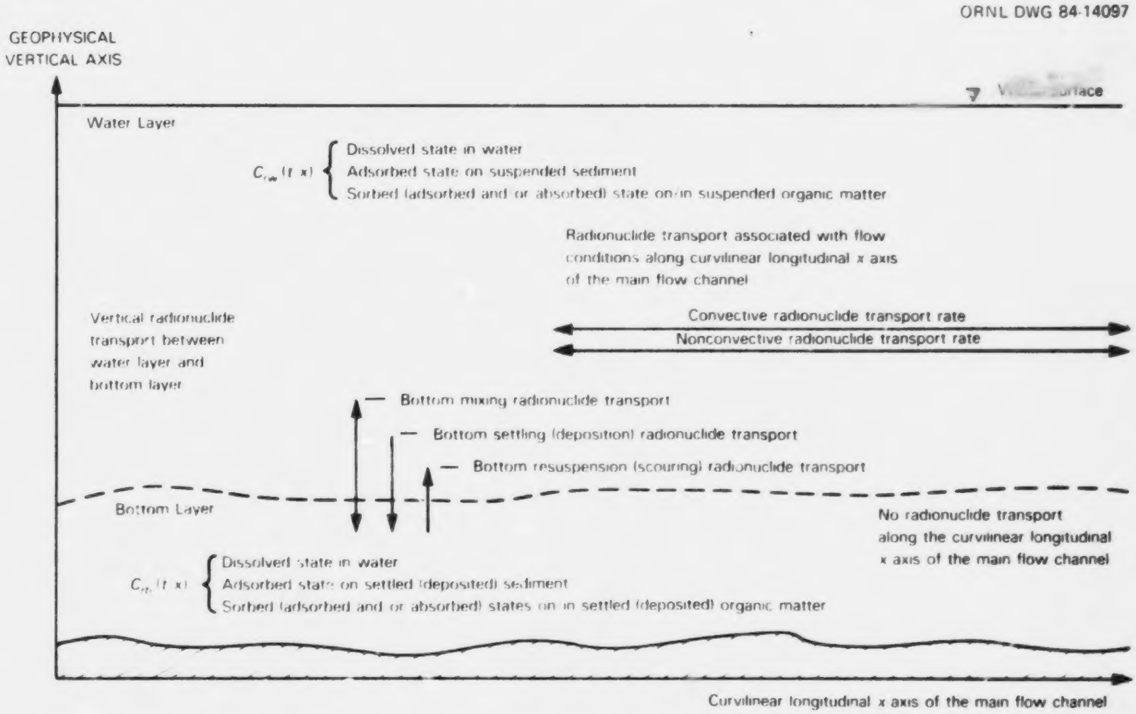
subregions along the river or estuary. Hence, in summary, the second important, long-term health safety problem requires information in the relatively simple, one-dimensional form as the value of the "bottom concentration of the radionuclide in the bottom layer" that can be transported only vertically between the "water layer" and the "bottom layer" with the contaminated bottom matter which can accumulate in different subregions along the main flow channel of a river or an estuary.

Therefore, in view of the pragmatic considerations associated with the two important health safety problems that must be investigated, during and after an accidental radiological release into the water body of a river or an estuary, the information, required by the radiological dose assessment calculations, can be provided by a fast-transient, one-dimensional, two-layer radionuclide transport model which can simulate (a) "water concentration of the radionuclide in the water layer" and (b) "bottom concentration of the radionuclide in the bottom layer," without necessitating the simulation of the detailed information about the radionuclide concentration conditions in different individual states.

The development of the fast-transient, one-dimensional, two-layer radionuclide transport model of the RADONE computer code considers that the radionuclide released into the water body is contained in two layers (Fig. 1.1) of the main flow channel of a river or an estuary.

1. *Water Layer:* The "water layer" is defined, according to relatively simple physical considerations, as the layer of water mixture that locally extends between the location of the physical bed bottom and the location of the water surface along the geophysical vertical direction, generally normal to the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GEOPHYSICAL VERTICAL AXIS
Water surface
Water Layer
$C_{rw}(t, x)$
Dissolved state in water
Adsorbed state on suspended sediment
Sorbed (adsorbed and or absorbed) state on/in suspended organic matter
Radionuclide transport associated with flow conditions along curvilinear longitudinal x axis of the main flow channel
Convective radionuclide transport rate
Nonconvective radionuclide transport rate
Vertical radionuclide transport between water layer and bottom layer
Bottom mixing radionuclide transport
Bottom settling (deposition) radionuclide transport
Bottom resuspension (scouring) radionuclide transport
Bottom Layer
No radionuclide transport along the curvilinear longitudinal x axis of the main flow channel
$C_{rb}(t, x)$
Dissolved state in water
Adsorbed state on settled (deposited) sediment
Sorbed (adsorbed and or absorbed) states on in settled (deposited) organic matter
Curvilinear longitudinal x axis of the main flow channel

Fig. 1.1. Schematic representation of radionuclide transport conditions in the water layer and bottom layer of the main flow channel.

curvilinear longitudinal *x*-axis of the main flow channel of the river or estuary. The water layer contains the radionuclide (a) in the dissolved state in water, (b) in the adsorbed state on suspended sediment, and (c) in the sorbed (adsorbed and/or absorbed) state on/in suspended organic matter, which collectively remain in the suspended state over the physical depth of water in the main flow channel. The important concept associated with the transport of the radionuclide in the water layer is that (a) the water, which contains the radionuclide in the dissolved state, (b) the suspended, multiple classes of sediment, which contain the radionuclide in multiple adsorbed states, and (c) the suspended, multiple organic matter, which contains the radionuclide in multiple sorbed (adsorbed and/or absorbed) states, collectively move, along the curvilinear longitudinal *x*-axis of the main flow channel, according to the fast-transient (tidal-transient) flow conditions in the main flow channel. Therefore, in the general conceptual sense, the radionuclide in the water layer, represented by the value of the water concentration of the radionuclide in the water layer $\overline{C}_{rw}(t,x)$ (Fig. 1.1), which corresponds to the averaged value over the radionuclide concentrations associated with all of its states of existence in the water layer, can be transported along the curvilinear, longitudinal *x*-axis of the main flow channel; and most importantly the radionuclide in the water layer can be transported predominantly by the convective transport phenomenon, which is controlled directly by the fast-transient (tidal-transient), one-dimensional, local flow conditions in the main flow channel of the river or estuary.

2. *Bottom Layer:* The "bottom layer" is defined, according to both physical and conceptual considerations, as a layer, with an arbitrarily selected hypothetical depth, which extends laterally and longitudinally over the curvilinear bed bottom of the main flow channel. The bottom layer contains the radionuclide (a) in the dissolved state in water, (b) in the adsorbed state on settled (deposited) sediment, and (c) in the sorbed (adsorbed and/or absorbed) state on/in settled (deposited) organic matter, which collectively remain in the settled (deposited) state within the arbitrarily selected depth. The important concept associated with the transport of the radionuclide in the bottom layer is that (a) the water, which contains the radionuclide in the dissolved state, (b) the settled (deposited) multiple classes of sediment, which contain the radionuclide in multiple adsorbed states, and (c) the settled (deposited) multiple organic matter, which contains the radionuclide in multiple sorbed (adsorbed and/or absorbed) states, cannot move—either individually or collectively—along the curvilinear longitudinal *x*-axis of the main flow channel. Therefore, conceptually, the only possible radionuclide transport, associated with the bottom layer, can occur along the geophysical vertical direction, generally normal to the curvilinear longitudinal *x*-axis of the main flow channel, between the water layer and the bottom layer. The overall vertical radionuclide transport, between the water layer and the bottom layer, consists of the cumulative effect of (1) bottom-mixing radionuclide transport, which includes the molecular diffusion and eddy-turbulent diffusion in the water, (2) bottom-settling (deposition) radionuclide transport, associated with the settling (depositing) multiple classes of sediment, which contain the radionuclide in multiple adsorbed states, and the settling (depositing) multiple organic matter, which contains the radionuclide in multiple sorbed (adsorbed and/or absorbed) states, and (3) bottom-resuspension (scouring) radionuclide transport, associated with the resuspending (scouring) multiple classes of sediment, which contain the radionuclide in multiple adsorbed states, and the resuspending (scouring) multiple organic matter, which contains the radionuclide in multiple sorbed (adsorbed and/or absorbed) states. Since all the transport mechanisms that contribute to the general vertical exchange phenomena, between the water layer and the bottom layer, depend on the local, bottom-mixing conditions (and, hence, the bottom shear-stress conditions), the local, net vertical radionuclide transport, between the water layer and the bottom layer, also depends on the fast-transient (tidal-transient), one-dimensional, local flow conditions in the main flow channel of the river of estuary.

Hence, based on the assumption of the two-layer concept, the mathematical development of the fast-transient (tidal-transient), one-dimensional, two-layer radionuclide transport model of the RADONE computer code considers two principal solution variables for representing the radionuclide concentration conditions, in the main flow channel of a river or an estuary, as

$\mathcal{C}_{rw}(t,x)$ = local, cross-section-averaged "water concentration of the radionuclide in the water layer," representing the net radiological unit per unit volume of water mixture in the water layer, which contains the radionuclide (1) in the dissolved state in water, (2) in the adsorbed state on suspended sediment, and (3) in the sorbed (adsorbed and/or absorbed) state on suspended organic matter in the water layer,

$\mathcal{C}_{rb}(t,x)$ = local, bottom-layer-depth-averaged (and approximately bottom-layer-cross-section-averaged) "bottom concentration of the radionuclide in the bottom layer," representing the net radiological unit per unit volume of water mixture in the bottom layer, which contains the radionuclide (1) in the dissolved state in water, (2) in the adsorbed state on settled (deposited) sediment, and (3) in the sorbed (adsorbed and absorbed) state on settled (deposited) organic matter in the bottom layer.

In summary, based on pragmatic considerations of the practical information that would be required for the investigation of the important short-term and long-term health safety problems, during and after an accidental radiological release into the water body, the subsequent development of the fast-transient (tidal-transient), one-dimensional, two-layer radionuclide transport model is designed to provide this practical information, as the computer simulation results of the RADONE computer code, in the form of temporal and spatial variations of (1) water concentration of the radionuclide in the water layer and (2) bottom concentration of the radionuclide in the bottom layer along the main flow channel of a controlled river or a tidal estuary.

2. SUMMARY OF COMPUTATIONAL EQUATIONS

The mathematical development of the fast-transient (tidal-transient), one-dimensional radionuclide transport model and the computational algorithm of its associated RADONE computer code for simulating the hydrodynamic conditions and the radionuclide concentration conditions in the water layer and in the bottom layer of a controlled-flow river or a tidal estuary are based on the general, fast-transient, one-dimensional discrete-element formulation of the Unified Transport Approach (UTA). The governing discrete-element equations and the computational algorithm for solving them associated with the hydrodynamic part of the RADONE model are presented in detail in the users manual report of ESTONE computer code [Eraslan (1983)]. Furthermore, the mathematical development of the governing discrete-element equations for the two-layer, radionuclide transport conditions, and the computational algorithm for solving them, are presented in detail for the more general, two-dimensional aquatic flow regions of lakes, reservoirs, rivers, estuaries, and coastal zones in the users manual for RADTWO computer code [Eraslan and Diament (1984)]. Therefore, this section is only intended to summarize the fundamental computational equations of the fast-transient (tidal-transient), one-dimensional, two-layer, discrete-element radionuclide transport model, so that the user can understand the special operational features of the RADONE computer in its applications to site-specific problems associated with radionuclide release scenarios in controlled-flow rivers and tidal estuaries.

2.1 SUMMARY DISCUSSION OF THE ONE-DIMENSIONAL DISCRETE-ELEMENT METHOD (DEM)

The one-dimensional, discrete-element formulation of the mathematical transport model considers computational elements as arbitrarily sized channel segments (Figs. 2.1 and 2.2) bounded by cross-sectional areas normal to the curvilinear longitudinal x-axis of the main flow channel of a river or an estuary. Each element consists of two parts, the upstream half-element and the downstream half-element, which represent the upstream half and downstream half of the channel segment (Figs. 2.1 and 2.2). At specific solution locations in elements and half-elements, RADONE simulates temporal (timewise) variations of the following principal flow variables:

1. water surface elevation (relative to an arbitrarily specified level),
2. channel flow rate (along the curvilinear longitudinal direction of the main flow channel),
3. water concentration of the radionuclide in the water layer, and
4. bottom concentration of the radionuclide in the bottom layer.

The mathematical system governing the solution of the four unknown principal flow variables is based on application of the discrete-element method to integral-form representations of the following physical laws:

1. principle of conservation of water mass for the solution of water surface elevation,
2. momentum principle, consisting of only the longitudinal component of the second law of motion associated with the flow of water (along the curvilinear longitudinal direction of the main flow channel) for the solution of channel flow rate,
3. pseudoconservation principle for the radionuclide in the water layer for the solution of the water concentration of the radionuclide in the water layer, and
4. pseudoconservation principle for the radionuclide in the bottom layer for the solution of the bottom concentration of the radionuclide in the bottom layer.

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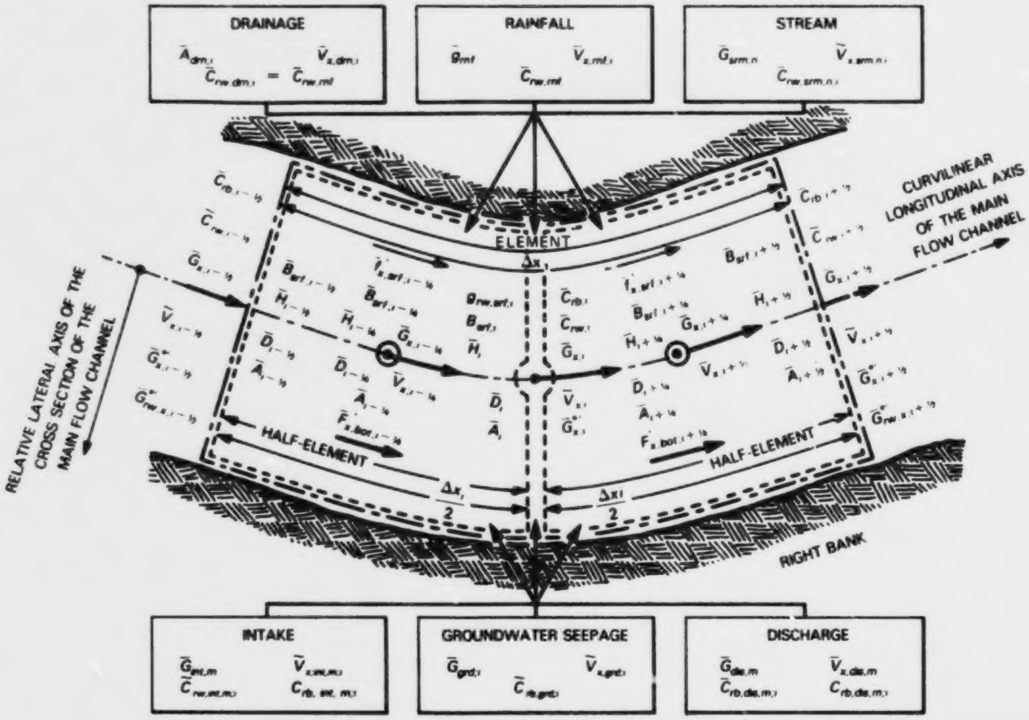
DRAINAGE
RAINFALL
STREAM
CURVILINEAR LONGITUDINAL AXIS OF THE MAIN FLOW CHANNEL
ELEMENT
RELATIVE LATERAL AXIS OF THE CROSS SECTION OF THE MAIN FLOW CHANNEL
HALF-ELEMENT
HALF-ELEMENT
RIGHT BANK
INTAKE
GROUNDWATER SEEPAGE
DISCHARGE

Fig. 2.1. Horizontal plane of computational element of a river or an estuary, showing half-elements and locations specified for principal solution variables and other variables.

The system of equations corresponding to the one-dimensional discrete-element formulation of the integral-form representations of the four physical laws constitutes the mathematical foundation of the fast-transient, one-dimensional, discrete-element mathematical transport model and the fundamental computational algorithm of the RADONE computer code. The detailed derivation of the governing system of discrete-element equations is presented in detail in the users manual for ESTONE computer code [Eraslan (1983)] and in the users manual RADTWO computer code [Eraslan and Diament (1984)] and therefore will not be repeated in this section.

2.2 DEFINITIONS OF MATHEMATICAL VARIABLES OF THE COMPUTATIONAL EQUATIONS

The variables used in the formulation of the one-dimensional, discrete-element mathematical transport model for simulating the hydrodynamic conditions and the two-layer radionuclide concentration conditions in the elements and half-elements (Figs. 2.1 and 2.2) of the main flow channel of a river or an estuary are presented in alphabetical order for the governing discrete-element computational equations of the RADONE computer code.

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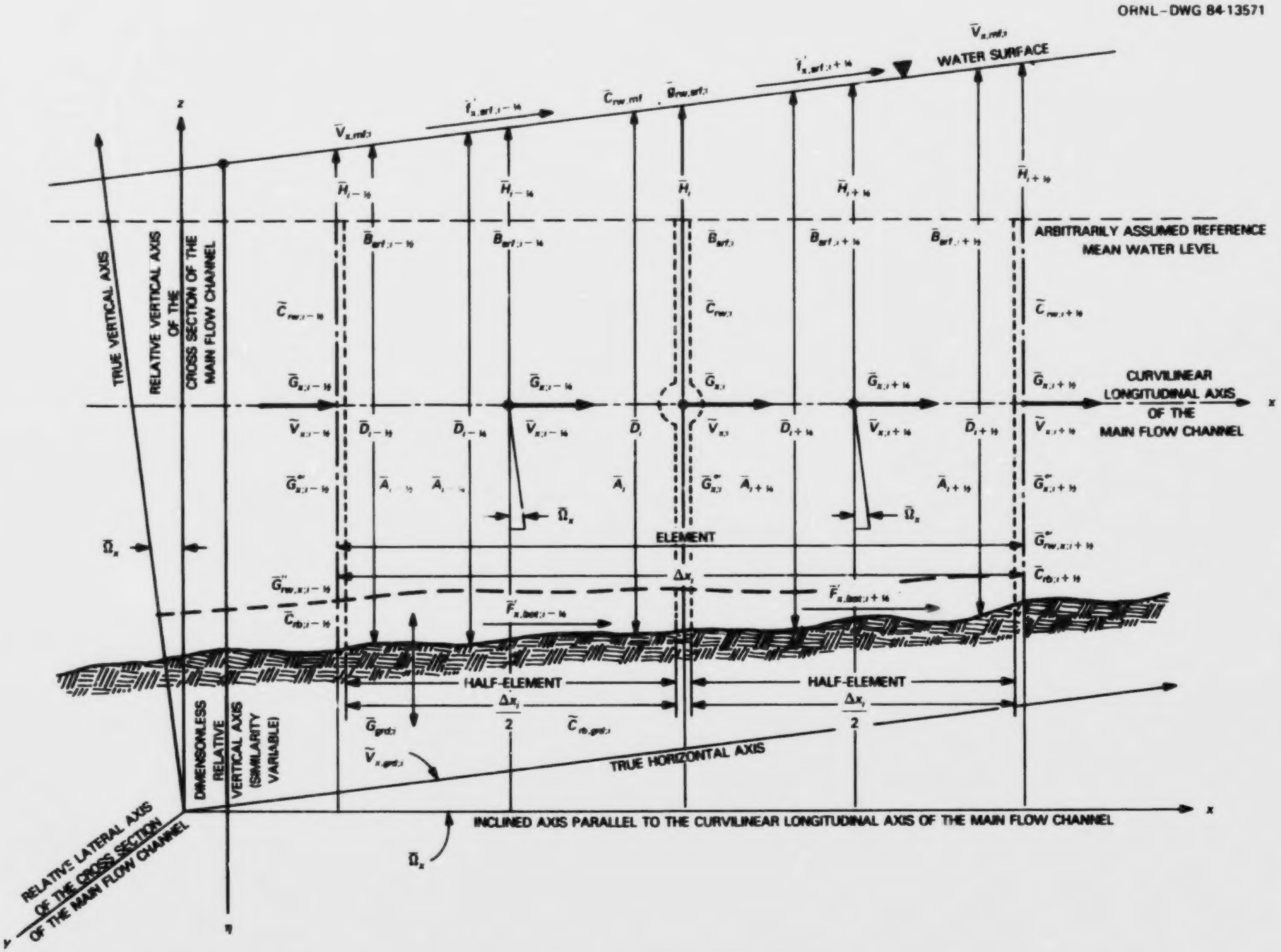
ORNL-DWG 84-13571
WATER SURFACE
ARBITRARILY ASSUMED REFERENCE MEAN WATER LEVEL
CURVILINEAR LONGITUDINAL AXIS OF THE MAIN FLOW CHANNEL
TRUE VERTICAL AXIS
RELATIVE VERTICAL AXIS OF THE CROSS SECTION OF THE MAIN FLOW CHANNEL
DIMENSIONLESS RELATIVE VERTICAL AXIS (SIMILARITY VARIABLE)
RELATIVE LATERAL AXIS OF THE CROSS SECTION OF THE MAIN FLOW CHANNEL
TRUE HORIZONTAL AXIS
INCLINED AXIS PARALLEL TO THE CURVILINEAR LONGITUDINAL AXIS OF THE MAIN FLOW CHANNEL
ELEMENT
HALF-ELEMENT
HALF-ELEMENT
Δx_i
$\frac{\Delta x_i}{2}$
$\frac{\Delta x_i}{2}$
$\bar{H}_{i-\frac{1}{2}}$
$\bar{H}_{i-\frac{1}{4}}$
$\bar{H}_i$
$\bar{H}_{i+\frac{1}{4}}$
$\bar{H}_{i+\frac{1}{2}}$
$\bar{B}_{srf;i-\frac{1}{2}}$
$\bar{B}_{srf;i-\frac{1}{4}}$
$\bar{B}_{srf;i}$
$\bar{B}_{srf;i+\frac{1}{4}}$
$\bar{B}_{srf;i+\frac{1}{2}}$
$\bar{C}_{rw;i-\frac{1}{2}}$
$\bar{C}_{rw;i}$
$\bar{C}_{rw;i+\frac{1}{2}}$
$\bar{C}_{rw,mf}$
$\bar{g}_{rw,srf;i}$
$\bar{V}_{x,mf;i}$
$f'_{x,srf;i-\frac{1}{4}}$
$f'_{x,srf;i+\frac{1}{4}}$
$\bar{G}_{x;i-\frac{1}{2}}$
$\bar{G}_{x;i-\frac{1}{4}}$
$\bar{G}_{x;i}$
$\bar{G}_{x;i+\frac{1}{4}}$
$\bar{G}_{x;i+\frac{1}{2}}$
$\bar{V}_{x;i-\frac{1}{2}}$
$\bar{V}_{x;i-\frac{1}{4}}$
$\bar{V}_{x;i}$
$\bar{V}_{x;i+\frac{1}{4}}$
$\bar{V}_{x;i+\frac{1}{2}}$
$\bar{D}_{i-\frac{1}{2}}$
$\bar{D}_{i-\frac{1}{4}}$
$\bar{D}_i$
$\bar{D}_{i+\frac{1}{4}}$
$\bar{D}_{i+\frac{1}{2}}$
$\bar{G}''_{x;i-\frac{1}{2}}$
$\bar{G}''_{x;i}$
$\bar{G}''_{x;i+\frac{1}{2}}$
$\bar{A}_{i-\frac{1}{2}}$
$\bar{A}_{i-\frac{1}{4}}$
$\bar{A}_i$
$\bar{A}_{i+\frac{1}{4}}$
$\bar{A}_{i+\frac{1}{2}}$
Ω_x
$\bar{G}''_{rw,x;i-\frac{1}{2}}$
$\bar{G}''_{rw,x;i+\frac{1}{2}}$
$\bar{C}_{rb;i-\frac{1}{2}}$
$\bar{C}_{rb;i+\frac{1}{2}}$
$\bar{F}'_{x,bot;i-\frac{1}{4}}$
$\bar{F}'_{x,bot;i+\frac{1}{4}}$
$\bar{G}_{grd;i}$
$\bar{C}_{rb,grd;i}$
$\bar{V}_{x,grd;i}$
z
x
x
y
η

Fig. 2.2. Vertical plane of computational element of a river or an estuary, showing half-elements and locations specified for principal solution variables and other variables.

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Subscripts of the mathematical variables used in the computational equations of the discrete-element formulation are as follows:

a = associated with the gravitational acceleration constant,
bl = associated with flow into or out of the bottom layer of the channel segment,
bot = associated with bottom layer of the channel segment,
dis = associated with discharge flow conditions at a plant,
drn = drainage conditions associated with land-surface drainage flow into the channel segment,
grd = groundwater conditions associated with groundwater seepage flow into or out of the channel segment,
i = index associated with the element representing averaged flow conditions in the channel segment,
$i - ¼$ = index associated with the upstream half-element representing averaged flow conditions in the upstream half of the channel segment,
$i + ¼$ = index associated with the downstream half-element representing averaged flow conditions in the downstream half of the channel segment,
$i - ½$ = index associated with the upstream enclosure surface of the element representing cross-section-averaged flow conditions at the upstream end of the channel segment,
$i + ½$ = index associated with the downstream enclosure surface of the element representing cross-section-averaged flow conditions at the downstream end of the channel segment,
int = intake flow conditions at a plant,
m = index associated with identifying a plant,
n = index associated with identifying a stream or tributary flowing into or out of the channel segment,
rb = associated with the radionuclide in the bottom layer of the channel segment,
rnf = rainfall conditions representing rainfall in the geographic (climatological) region of the main flow channel,
rw = associated with the radionuclide in the water layer of the channel segment,
srf = associated with the surface conditions at the water surface of the channel segment,
srm = associated with a stream or tributary flowing into or out of the channel segment,
w = associated with water,
wl = associated with flow into or out of the water layer of the channel segment, and
x = direction along the curvilinear longitudinal axis of the main flow channel.

The subscript notation of the mathematical variables is unconventional because it utilizes the semicolon (;), which is not related to the conventional contravariant operation associated with tensor analysis. This subscript notation is specifically designed for UTA discrete-element mathematical models, which can simultaneously predict different water quality conditions, including numerous concentrations of matter (e.g., salt, chemical constituents, sediment, radionuclides, and biological organisms). The semicolon subscript can conveniently separate subscripts that identify flow variables from indices associated with discrete elements of channel segments.

Mathematical variables used in the computational equations of the discrete-element formulation are

$\overline{A}_{drn:i}$ = specified drainage area associated with drainage flow into element i of the channel segment (ft^2),
$\overline{A}_i$ = cross-sectional area at the center of element i representing mean area of the cross section of the channel segment (ft^2),

$\overline{A}_{i-1/4}$ = cross-sectional area at the center of the upstream half-element $i - 1/4$, representing mean area of the cross section of the upstream half of the channel segment (ft^2),

$\overline{A}_{i+1/4}$ = cross-sectional area at the center of the downstream half-element $i + 1/4$, representing mean area of the cross section of the downstream half of the channel segment (ft^2),

$\overline{A}_{i-1/2}$ = cross-sectional area of the upstream enclosure surface at $i - 1/2$ of element i, representing mean area of the upstream cross section of the channel segment (ft^2),

$\overline{A}_{i+1/2}$ = cross-sectional area of the downstream enclosure surface at $i + 1/2$ of element i, representing mean area of the downstream cross section of the channel segment (ft^2),

$\overline{B}_{srf;i}$ = lateral surface width at the center of element i, representing mean lateral width of the surface of the channel segment (ft^2),

$\overline{B}_{srf;i-1/4}$ = lateral surface width at the center of the upstream half-element $i - 1/4$, representing mean lateral width of the surface of the upstream half of the channel segment (ft),

$\overline{B}_{srf;i+1/4}$ = lateral surface width at the center of the downstream half-element $i + 1/4$, representing mean lateral width of the surface of the downstream half of the channel segment (ft),

$\overline{C}_{rb,dis,m,bl;i}$ = specified or evaluated value of the bottom concentration of the radionuclide associated with the discharge flow of plant m discharged into the bottom layer in element i of the channel segment (radiologic unit/ft^3),

$\tilde{\overline{C}}_{rb,grd,bl;i}$ = bottom concentration of the radionuclide of the groundwater seepage flow determined according to the generalized upwind-differenced value and based on either specified bottom concentration of the radionuclide of inflowing groundwater or, for outflowing seepage conditions, bottom concentration of the radionuclide in the bottom layer in element i of the channel segment (radiologic unit/ft^3),

$\overline{C}_{rb;i}$ = bottom concentration of the radionuclide in the bottom layer at the center of element i, representing the mean bottom concentration of the radionuclide in the bottom layer in the channel segment (radiologic unit/ft^3),

$\dot{\overline{C}}_{rb;i}$ = radiological decay rate of the bottom concentration of the radionuclide in the bottom layer (radiologic unit $ft^{-3}\,h^{-1}$),

$\tilde{\overline{C}}_{rb,int,m,bl;i}$ = bottom concentration of the radionuclide, determined according to the generalized upwind-differenced value, associated with the intake flow of plant m withdrawn from the bottom layer in the element i of the channel segment (radiologic unit/ft^3),

$\tilde{\overline{C}}_{rb,srm,bl;i}$ = bottom concentration of the radionuclide associated with the flow of stream or tributary n, determined according to the generalized upwind-differenced value and based on either specified bottom concentration of the radionuclide of the inflowing stream or tributary or, for outflowing stream conditions, the bottom concentration of the radionuclide in the bottom layer in element i of the channel segment (radiologic unit/ft^3),

$\overline{C}_{rw,dis,m,wl;i}$ = specified or evaluated value of the water concentration of the radionuclide associated with the discharge flow of plant m discharged into the water layer in element i of the channel segment (radiologic unit/ft^3),

$\tilde{\overline{C}}_{rw,drn;i}$ = specified water concentration of the radionuclide associated with the drainage flow into or out of the element i of the channel segment (radiologic unit/ft^3),

$\tilde{\overline{C}}_{rw,grd,wl;i}$ = water concentration of the radionuclide of the groundwater seepage flow determined according to the generalized upwind-differenced value and based on either specified water concentration of the radionuclide of inflowing groundwater or, for outflowing seepage conditions, water concentration of the radionuclide in the water layer in element i of the channel segment (radiologic unit/ft^3),

$\bar{C}_{rw;i}$ = water concentration of the radionuclide in the water layer at the center of the element *i*, representing the mean water concentration of the radionuclide in the water layer in the channel segment (radiologic unit/ft^3),

$\dot{\bar{C}}_{rw;i}$ = radiological decay rate of the water concentration of the radionuclide in the water layer (radiologic unit ft^{-3} h^{-1}),

$\tilde{C}_{rw;i-1/2}$ = water concentration of the radionuclide in the water layer at the upstream enclosure surface at $i - 1/2$ of element *i*, representing the upwind-differenced value of the water concentration of the radionuclide in the water layer at the upstream end of the channel segment (radiologic unit/ft^3),

$\tilde{C}_{rw;i+1/2}$ = water concentration of the radionuclide in the water layer at the downstream enclosure surface at $i + 1/2$ of element *i*, representing the upwind-differenced value of water concentration of the radionuclide in the water layer at the upstream end of the channel segment (radiologic unit/ft^3),

$\tilde{C}_{rw,int,m,wl;i}$ = water concentration of the radionuclide determined according to the generalized upwind-differenced value, associated with the intake flow of plant *m*, withdrawn from the water layer in the element *i* of the channel segment (radiologic unit/ft^3),

$\bar{C}_{rw,rnf}$ = water concentration of the radionuclide in the rainfall in the geographic (climatological) region of the main flow channel (radiologic unit/ft^3),

$\tilde{C}_{rw,srm,n,wl;i}$ = water concentration of the radionuclide associated with the flow of stream or tributary *n*, determined according to the generalized upwind-differenced value and based on either specified water concentration of the radionuclide of the inflowing stream or tributary or, for outflowing stream conditions, the water concentration of the radionuclide in the water layer in element *i* of the channel segment (radiologic unit/ft^3),

D_{bl} = specified constant depth of the bottom layer of the main flow channel (ft),

$[\bar{F}_{bl}(\bar{C}_{rb})]_i$ = the right-hand-side solution function of the discrete-element equation for bottom concentration of the radionuclide in the bottom layer in element *i* [Eq. (2.22), radiologic unit ft^{-3} h^{-1}],

$[\bar{F}_{bot}(\bar{C}_{rb})]_i$ = the part representing the net bottom radionuclide transport effect at the top of the bottom layer in element *i*, between the water layer and the bottom layer, of the right-hand-side solution function of the discrete-element equation for bottom concentration of the radionuclide in the bottom layer in element *i* [Eqs. (2.18) and (2.2), radiologic unit ft^{-3} h^{-1}],

$[\bar{F}_{bot}(\bar{C}_{rw})]_i$ = the part representing the net bottom radionuclide transport effect of the bottom of the water layer in element *i*, between the water layer and the bottom layer, of the right-hand-side solution function of the discrete-element equation for water concentration of the radionuclide in the water layer in element *i* [Eqs. (2.8) and (2.13), radiologic unit ft^{-3} h^{-1}],

$[\bar{F}_{cnv}(\bar{C}_{rw})]_i$ = the part representing the convective radionuclide transport (along the curvilinear longitudinal *x*-axis of the main flow channel of the right-hand-side solution function of the discrete-element equation for water concentration of the radionuclide in the water layer in element *i* [Eqs. (2.5) and (2.13), radiologic unit ft^{-3} h^{-1}],

$[\bar{F}_{grd}(\bar{C}_{rb})]_i$ = the part representing the radionuclide transport effect, associated with groundwater seepage flow into or out of the main flow channel in the bottom layer in element *i*, of the right-hand-side solution function of the discrete-element equation for bottom concentration of the radionuclide in the bottom layer in element *i* [Eqs. (2.17) and (2.22), radiologic unit ft^{-3} h^{-1}],

$[F_{grd}(\mathcal{C}_{rw})]_i$ = the part representing the radionuclide transport effect, associated with groundwater seepage flow into or out of the main flow channel in the water layer in element *i*, of the right-hand-side solution function of the discrete-element equation for water concentration of the radionuclide in the water layer in element *i* [Eqs. (2.7) and (2.13), radiologic unit $\mathrm{ft}^{-3}\,\mathrm{h}^{-1}$],

$[F_{plt}(\mathcal{C}_{rb})]_i$ = the part representing the radionuclide transport effect, associated with the intake flow rate and discharge flow rate of plant *m* into and/or out of the main flow channel in the bottom layer in element *i*, of the right-hand-side solution function of the discrete-element equation for bottom concentration of the radionuclide in the bottom layer in element *i* [Eqs. (2.20) and (2.22), radiologic unit $\mathrm{ft}^{-3}\,\mathrm{h}^{-1}$],

$[F_{plt}(\mathcal{C}_{rw})]_i$ = the part representing the radionuclide transport effect, associated with the intake flow rate and the discharge flow rate of plant *m* into and/or out of the main flow channel in the water layer in element *i*, of the right-hand-side solution function of the discrete-element equation for water concentration of the radionuclide in the water layer in element *i* [Eqs. (2.11) and (2.13), radiologic unit $\mathrm{ft}^{-3}\,\mathrm{h}^{-1}$],

$[F_{rad}(\mathcal{C}_{rb})]_i$ = the part representing the radiological decay effect of the radionuclide in the bottom layer in element *i* of the right-hand-side solution function of the discrete-element equation for bottom concentration of the radionuclide in the bottom layer in element *i* [Eqs. (2.21) and (2.22), radiologic unit $\mathrm{ft}^{-3}\,\mathrm{h}^{-1}$],

$[F_{rad}(\mathcal{C}_{rw})]_i$ = the part representing the radiological decay effect of the radionuclide in the water layer in element *i* of the right-hand-side solution function of the discrete-element equation for water concentration of the radionuclide in the water layer in element *i* [Eqs. (2.12) and (2.13), radiologic unit $\mathrm{ft}^{-3}\,\mathrm{h}^{-1}$],

$[F_{srf}(\mathcal{C}_{rw})]_i$ = the part representing the net effect of radionuclide transport, associated with the rainfall in the geographic (climatological) region of the main flow channel, including the direct radionuclide transport rate into the main flow channel, resulting from rainfall on the water surface and the indirect radionuclide transport rate into the main flow channel, resulting from drainage inflow rate, controlled by the rainfall rate and the radionuclide concentration conditions in the drainage areas in the geographical region, in the water layer in element *i*, of the right-hand-side solution function of the discrete-element equation for water concentration of the radionuclide in the water layer in element *i* [Eqs. (2.9) and (2.13), radiologic unit $\mathrm{ft}^{-3}\,\mathrm{h}^{-1}$],

$[F_{srm}(\mathcal{C}_{rb})]_i$ = the part representing the convective radionuclide transport rate associated with the flow of stream or tributary *n*, into or out of the main flow channel in the bottom layer in element *i*, of the right-hand-side solution function of the discrete-element equation for bottom concentration of the radionuclide in the bottom layer in element *i* [Eqs. (2.19) and (2.22), radiologic unit $\mathrm{ft}^{-3}\,\mathrm{h}^{-1}$],

$[F_{srm}(\mathcal{C}_{rw})]_i$ = the part representing the convective radionuclide transport rate associated with the flow of stream or tributary *n*, into or out of the main flow channel in the water layer in element *i*, of the right-hand-side solution function of the discrete-element equation for water concentration of the radionuclide in the water layer in element *i* [Eqs. (2.10) and (2.13), radiologic unit $\mathrm{ft}^{-3}\,\mathrm{h}^{-1}$],

$[F_{trb}(\mathcal{C}_{rw})]_i$ = the part representing the nonconvective radionuclide transport rate (as the combination of molecular radionuclide transport rate, convection-defect radionuclide transport rate, and eddy-turbulent radionuclide transport rate, along the curvilinear longitudinal x-axis of the main flow channel) in the water layer in element i of the right-hand-side solution function of the discrete-element equation for water concentration of the radionuclide in the water layer in element i [Eqs. (2.6) and (2.13), radiologic unit ft^{-3} h^{-1}],

$[\bar{F}_{wl}(\bar{C}_{rw})]_i$ = the right-hand-side solution function of the discrete-element equation for water concentration of the radionuclide in the bottom layer in element i [Eq. (2.13), radiologic unit ft^{-3} h^{-1}],

$\bar{F}'_{x,bot;i-1/4}$ = bottom drag force per unit length (along the curvilinear longitudinal x-axis of the main flow channel) at the center of the upstream half-element $i - 1/4$, representing net value of bottom drag force per unit length and based on bed conditions of the upstream half of the channel segment [ft^3/h^2 (modified flow-rate-consistent units)],

$\bar{F}'_{x,bot;i+1/4}$ = bottom drag force per unit length at the center of the downstream half-element $i + 1/4$, representing net value of bottom drag force per unit length and based on bed conditions of the downstream half of the channel segment [ft^3/h^2 (modified flow-rate-consistent units)],

$\bar{J}'_{x,srf;i-1/4}$ = surface wind stress (along the curvilinear longitudinal x-axis of the main flow channel) at the center of the upstream half-element $i - 1/4$, representing mean value of surface wind stress and based on speed and direction of wind relative to flow conditions on the water's surface in the upstream half of the channel segment [ft^2/h^2 (modified flow-rate-consistent units)],

$\bar{J}'_{x,srf;i+1/4}$ = surface wind stress at the center of the downstream half-element $i + 1/4$, representing mean value of surface wind stress and based on speed and direction of wind relative to flow conditions on the water surface in the downstream half of the channel segment [ft^2/h^2 (modified flow-rate-consistent units)],

$\bar{G}_{dis,m}$ = discharge flow rate of plant m into the main flow channel (ft^3/h),

$\bar{G}_{dis,m,bl;i}$ = portion of the discharge flow rate of plant m discharged into the bottom layer in element i of the channel segment (ft^3/h),

$\bar{G}_{dis,m,wl;i}$ = portion of the discharge flow rate of plant m discharged into the water layer in element i of the channel segment (ft^3/h),

$\bar{G}_{grd;i}$ = groundwater seepage flow rate into or out of element i of the channel segment (ft^3/h),

$\bar{G}_{grd,bl;i}$ = groundwater seepage flow rate into or out of the bottom layer in element i of the channel segment (ft^3/h),

$\bar{G}_{grd,wl;i}$ = groundwater seepage flow rate into or out of the water layer in element i of the channel segment (ft^3/h),

$\bar{G}_{int,m}$ = intake flow rate of plant m into or out of the main flow channel (flow into the power plant is a negative value) (ft^3/h),

$\bar{G}_{rb,bot;i}$ = net bottom radionuclide transport rate between the water layer and the bottom layer at the top of the bottom layer in element i, representing the cumulative effect of radionuclide transport from the water layer into the bottom layer in the channel segment (radiologic unit ft^{-2} h^{-1}),

$\bar{G}_{rw,bot;i}$ = net bottom radionuclide transport rate between the water layer and the bottom layer at the bottom of the water layer in element i, representing the cumulative effect of radionuclide transport from the bottom layer into the water layer in the channel segment (radiologic unit ft^{-2} h^{-1}),

$\overline{G}_{int,m,bl;i}$ = portion of the intake flow rate of plant *m* withdrawn from the bottom layer in element *i* of the channel segment (ft^3/h),

$\overline{G}_{int,m,wl;i}$ = portion of intake flow rate of plant *m* withdrawn from the water layer of element *i* of the channel segment (ft^3/h),

$\overline{G}_{rw,x;i-1/2}$ = nonconvective radionuclide transport rate (along the curvilinear longitudinal *x*-axis of the main flow channel), consisting of the combination of molecular, convection-defect and eddy-turbulent radionuclide transport rates, at the upstream enclosure surface at $i - 1/2$ of element *i* and representing the net nonconvective radionuclide transport rate in the water layer at the upstream end of the channel segment (radiologic unit/h),

$\overline{G}_{rw,x;i+1/2}$ = nonconvective radionuclide transport rate (along the curvilinear longitudinal *x*-axis of the main flow channel), consisting of the combination of molecular, convection-defect and eddy-turbulent radionuclide transport rates, at the downstream enclosure surface at $i + 1/2$ of element *i* and representing the net nonconvective radionuclide transport rate in the water layer at the upstream end of the channel segment (radiologic unit/h),

$\overline{G}_{srm,n}$ = flow rate of stream or tributary *n* into or out of the main flow channel (ft^3/h),

$\overline{G}_{srm,n,bl;i}$ = portion of the flow rate of stream or tributary *n* into or out of the bottom layer of element *i* of the channel segment (ft^3/h),

$\overline{G}_{srm,n,wl;i}$ = portion of the flow rate of stream or tributary *n* into or out of the water layer of element *i* of the channel segment (ft^3/h),

$\overline{G}_{x;i}$ = channel flow rate (along the curvilinear longitudinal *x*-axis of the main flow channel) at the center of element *i*, representing net value of the channel flow rate in the channel segment (ft^3/h),

$\overline{G}_{x;i-1/4}$ = channel flow rate at the center of the upstream half-element $i - 1/4$, representing net value of the channel flow rate in the upstream half of the channel segment (ft^3/h),

$\overline{G}_{x;i+1/4}$ = channel flow rate at the center of the downstream half-element $i + 1/4$, representing net value of the channel flow rate in the downstream half of the channel segment (ft^3/h),

$\overline{G}_{x;i-1/2}$ = channel flow rate at the upstream enclosure surface at $i - 1/2$ of element *i*, representing net value of the channel flow rate at the upstream end of the channel segment (ft^3/h),

$\overline{G}_{x;i+1/2}$ = channel flow rate at the downstream enclosure surface at $i + 1/2$ of element *i*, representing net value of the channel flow rate at the downstream end of the channel segment (ft^3/h),

$\overline{G}^{\bullet\prime}_{x;i}$ = nonconvective momentum transport rate (along the curvilinear longitudinal *x*-axis of the main flow channel) consisting of only the convection-defect momentum transport rate with negligible eddy-turbulent momentum transport rate at the center of discrete-element *i* and representing net value of the convection-defect momentum transport rate in the channel segment (ft^4/h^2),

$\overline{G}^{\bullet\prime}_{x;i-1/2}$ = nonconvective momentum transport rate consisting of only the convection-defect momentum transport rate with negligible eddy-turbulent momentum transport rate at the upstream enclosure surface at $i - 1/2$ of element *i* and representing net value of the convection-defect momentum transport rate at the upstream end of the channel segment (ft^4/h^2),

$\overline{G}^{\bullet\prime}_{x;i+1/2}$ = nonconvective momentum transport rate consisting of only the convection-defect momentum transport rate with negligible eddy-turbulent momentum transport rate at the downstream enclosure surface at $i + 1/2$ of element *i* and representing net value of the convection-defect momentum transport rate at the downstream end of the channel segment (ft^4/h^2),

g_a = gravitational acceleration constant (32.2×3600^2 ft/h^2),

$\bar{g}_{rnf}$ = rainfall rate per unit area in the geographic (climatological) region of the main flow channel (ft/h),

$\bar{H}_i$ = water surface elevation at the center of element i, representing mean value of the water surface elevation in the channel segment (ft),

$\bar{H}_{i-\frac{1}{4}}$ = water surface elevation at the center of the upstream half-element $i - \frac{1}{4}$, representing mean value of the water surface elevation in the upstream half of the channel segment (ft),

$\bar{H}_{i+\frac{1}{4}}$ = water surface elevation at the center of the downstream half-element $i + \frac{1}{4}$, representing mean value of the water surface elevation in the downstream half of the channel segment (ft),

$\bar{H}_{i-\frac{1}{2}}$ = water surface elevation at the upstream enclosure surface at $i - \frac{1}{2}$ of element i, representing mean value of the water surface elevation at the upstream end of the channel segment (ft),

$\bar{H}_{i+\frac{1}{2}}$ = water surface elevation at the downstream enclosure surface at $i + \frac{1}{2}$ of element i, representing mean value of the water surface elevation at the downstream end of the channel segment (ft),

N = total number of elements corresponding to the total number of arbitrarily sized channel segments that collectively span the curvilinear longitudinal length of the main flow channel,

t = time (h),

$\bar{V}_{x,dis;m}$ = velocity of discharge flow of plant m (along the curvilinear longitudinal x-axis of the main flow channel) (ft/h),

$\bar{V}_{x,drn;i}$ = velocity of drainage flow into element i of the channel segment (along the curvilinear longitudinal x-axis of the main flow channel) (ft/h),

$\tilde{V}_{x,grd;i}$ = velocity of groundwater seepage flow determined according to the generalized upwind-differenced value and based on either the specified velocity component of inflowing groundwater or, for outflowing seepage conditions, velocity in element i of the channel segment (along the curvilinear longitudinal x-axis of the main flow channel) (ft/h),

$\tilde{V}_{x;i}$ = channel flow velocity at the enclosure surface at the center of element i determined according to the upwind-differenced value and based on either the velocity condition in the upstream half-element $i - \frac{1}{4}$ or the velocity condition in the downstream half-element $i + \frac{1}{4}$, which correspond to velocity conditions in either the upstream half or downstream half of the channel segment (along the curvilinear longitudinal x-axis of the main flow channel) (ft/h),

$\tilde{V}_{x;i-\frac{1}{2}}$ = channel flow velocity at the upstream enclosure surface at $i - \frac{1}{2}$ of the element i, representing the upwind-differenced value of the velocity at the upstream end of the channel segment (along the curvilinear longitudinal x-axis of the main flow channel) (ft/h),

$\tilde{V}_{x;i+\frac{1}{2}}$ = channel flow velocity at the downstream enclosure surface $i + \frac{1}{2}$ of element i, representing the upwind-differenced value of the velocity at the downstream end of the channel segment (along the curvilinear longitudinal x-axis of the main flow channel) (ft/h),

$\widetilde{V}_{x,int,m;i}$ = velocity of the intake flow of plant *m* determined according to the generalized upwind-differenced value and based on the velocity in intake element *i* of the channel segment (along the curvilinear longitudinal *x*-axis of the main flow channel) (ft/h),

$\overline{V}_{x,rnf;i}$ = velocity of rainfall determined according to rainfall and wind conditions relative to the direction of the main flow channel at the center of element *i* of the channel segment (along the curvilinear longitudinal *x*-axis of the main flow channel) (ft/h),

$\widetilde{V}_{x,srm,n;i}$ = velocity of the flow of stream or tributary *n* determined according to the generalized upwind-differenced value and based on either specified velocity of the inflowing stream or, for outflowing stream conditions, the velocity in element *i* of the channel segment (along the curvilinear longitudinal *x*-axis of the main flow channel) (ft/h),

Δx_i = curvilinear length of the discrete element *i* (along the curvilinear longitudinal *x*-axis of the main flow channel), representing curvilinear length of the channel segment (ft),

$\delta_{dis,m;i}$ = Kronecker delta for indicating location of the discharge of plant *m;* that is, when $\delta_{dis,m;i}$

= 0: location of the discharge of plant *m* is not in element *i* of the channel segment;
= 1: location of the discharge of plant *m* is in element *i* of the channel segment,

$\delta_{int,m;i}$ = Kronecker delta for indicating location of the intake of plant *m;* that is, when $\delta_{int,m;i}$

= 0: location of the intake of plant *m* is not in element *i* of the channel segment;
= 1: location of the intake of plant *m* is in element *i* of the channel segment,

$\delta_{srm,n;i}$ = Kronecker delta for indicating location of stream or tributary *n;* that is, when $\delta_{srm,n;i}$

= 0: location of stream *n* is not in element *i* of the channel segment;
= 1: location of stream *n* is in element *i* of the channel segment,

$\bar{\rho}_w$ = constant (approximately) mass density of the representative water mixture (including water, suspended sediment and suspended organic matter, etc.) in the main flow channel (suggested value, 62.4 lb_m/ft^3),

Γ_i = bed contour of the main flow channel in the element *i* of the channel segment (ft), and

$\overline{\Omega}_x$ = small angle (or the sine of the small angle) of inclination of the curvilinear longitudinal *x*-axis of the main flow channel relative to the true horizontal axis (degree) (Fig. 2.2).

These mathematical variables are associated with the fundamental, discrete-element computational equations of the RADONE computer code, which are presented later in this section. Additional auxiliary mathematical variables are defined in Sect. 3, which presents the development of the nonconvective transport model, and in Sect. 4, which presents the formulation of specified transport conditions that are based on input data to RADONE computer code.

2.3 DISCRETE-ELEMENT FORMS OF THE COMPUTATIONAL EQUATIONS

Formulation of the computational equations of the RADONE computer code is based on the application of the one-dimensional form of the general discrete-element method [e.g., Eraslan (1983); Eraslan, Lin, and Sharp (1983)], which is based on the direct computer simulation approach in the modeling of physical and biological transport phenomena in aquatic flow regions. This approach is common to the formulation of all the governing systems of computational equations of all mathematical transport models developed in the Unified Transport Approach (UTA) project [Eraslan et al. (1976); Eraslan and Witten (1984)].

In the application of the one-dimensional form of the discrete-element method, the longitudinal curvilinear length of the main flow channel of a river or an estuary is divided into a specified number, N, or arbitrarily sized channel segments (Figs. 2.1 and 2.2). The channel segments are considered discrete elements and are designated by $i = 1, 2, ..., N$; collectively, they span the length of the main flow channel, which corresponds to the distance (along the curvilinear longitudinal x-axis of the main flow channel) between two arbitrarily specified upstream and downstream cross sections of the river or estuary. Each element is divided into two parts, the upstream half-element $i - ¼$ and the downstream half-element $i + ¼$, which equally divide the length (along the curvilinear longitudinal x-axis of the main flow channel) of an element; the two parts represent the upstream half and downstream half of the channel segment. In the development of computational equations of the one-dimensional transport model, the three-dimensional geometric characteristics of each element are carefully considered based on the detailed geometry of the bed contour of the main flow channel at the location of the segment along the curvilinear longitudinal axis of the river or estuary.

Development of the governing discrete-element equations for the solution of the four principal solution variables (water surface elevation, channel flow rate, water concentration of the radionuclide in the water layer and bottom concentration of the radionuclide in the bottom layer) is based on rigorous mathematical formulation of the volume and surface integrals of the three physical laws (principle of conservation of water mass, longitudinal component of the second law of motion as the momentum principle associated with the flow of water, and pseudoconservation principle for the radionuclide). These physical laws are applied rigorously in evaluating the integrals over the volumes and the enclosure surfaces of (1) the element corresponding to the arbitrarily sized channel segment and (2) the upstream half-element $i - ¼$ and the downstream half-element $i + ¼$ corresponding to the upstream half and the downstream half of the channel segment with accurately specified geometric characteristics of the main flow channel. Furthermore, in the application of the pseudoconservation principle for the radionuclide, the integrals over the volumes and the enclosure surfaces are considered in two layers, consisting of the water and the bottom layer in each element of the main flow channel.

2.3.1 Discrete-Element Equation for Water Surface Elevation

The application of the discrete-element method to the integral form of the conservation principle for water mass in element i, corresponding to an arbitrarily sized channel segment (Figs. 2.1 and 2.2), results in a discrete-element equation for the solution of water depth in element i. However, for the simulation of flow conditions in a river or an estuary, it is generally more convenient to consider elevation of the water surface relative to an appropriately specified mean water level, which by definition remains constant along the curvilinear longitudinal axis of the main flow channel. Hence, formulation of the discrete-element mathematical model includes the specified distribution (along the curvilinear longitudinal axis x of the main flow channel) of temporally constant mean water depth based on a specified mean water level (relative to an arbitrarily specified level). In the discrete-element formulation of the integral form of the conservation principle for water mass in element i, the temporally constant mean water depth, associated with the arbitrarily specified mean water level, is subtracted from the temporally varying water depth in element i to obtain the discrete-element equation for water surface elevation (relative to an arbitrarily specified level):

$$\begin{aligned}\frac{\partial \overline{H}_i}{\partial t} &= \frac{1}{\Delta x_i \overline{B}_{srf;i}}(\overline{G}_{x;i-½} - \overline{G}_{x;i+½}) + \overline{g}_{rnf}\left(1 + \frac{\overline{A}_{drn;i}}{\Delta x_i \overline{B}_{srf;i}}\right) + \frac{\delta_{srm,n;i}}{\Delta x_i \overline{B}_{srf;i}}\overline{G}_{srm,n} \\ &+ \frac{1}{\Delta x_i \overline{B}_{srf;i}}\overline{G}_{grd;i} + \frac{\delta_{int,m;i}}{\Delta x_i \overline{B}_{srf;i}}\overline{G}_{int,m} + \frac{\delta_{dis,m;i}}{\Delta x_i \overline{B}_{srf;i}}\overline{G}_{dis,m} \; . \qquad (2.1)\end{aligned}$$

The mathematical and computational characteristics of the discrete-element equation for water surface elevation [Eq. (2.1)] are discussed in detail in the users manual of ESTONE computer code [Eraslan (1983)].

2.3.2 Discrete-Element Equation for Channel Flow Rate

Discrete-element formulation of the integral form of the longitudinal component of the second law of motion, the momentum principle associated with the flow of water, requires careful consideration of special physical stability characteristics of free-surface flow conditions in controlled rivers and tidal estuaries. Based on consideration of these characteristics, the application of the discrete-element method utilizes two parts of each element, the upstream half-element and the downstream half-element, in the development of the discrete-element computational equation for flow rate.

The mathematical formulation considers the integral form of the longitudinal component of the second law of motion (along the curvilinear longitudinal *x*-axis of the main flow channel) in two parts: (1) for water contained in the upstream half-element and (2) for water contained in the downstream half-element. Hence, two sets of discrete-element equations are formulated for the solution of flow rates in two half-elements of each segment of the main flow channel. Consequently, the numerical solution algorithm of RADONE computer code utilizes twice as many computational points for the solution of flow rate as for the solution of water surface elevation.

Applying the discrete-element method to the integral form of the longitudinal component of the second law of motion (along the curvilinear longitudinal *x*-axis of the main flow channel) for water contained in the upstream half-element $i - \frac{1}{4}$, the discrete-element equation for channel flow rate becomes

$$
\begin{aligned}
\frac{\partial \overline{G}_{x;i-\frac{1}{4}}}{\partial t} = {} & \frac{2}{\Delta x_i}\left(\overline{G}_{x;i-\frac{1}{2}}\widetilde{V}_{x;i-\frac{1}{2}} - \overline{G}_{x;i}\widetilde{V}_{x;i}\right) + \frac{2g_a}{\Delta x_i}\left[\overline{A}_{i-\frac{1}{2}}\left(\overline{H}_{i-\frac{1}{2}} - \overline{H}_{i-\frac{1}{4}}\right) - \overline{A}_i\left(\overline{H}_i - \overline{H}_{i-\frac{1}{4}}\right)\right] \\
& + g_a\overline{A}_{i-\frac{1}{4}}\overline{\Omega}_x + \frac{2}{\Delta x_i}\left(\overline{G}^{*\prime}_{x;i-\frac{1}{2}} - \overline{G}^{*\prime}_{x;i}\right) + \overline{F}_{x,bot;i-\frac{1}{4}} \\
& + \overline{B}_{srf;i-\frac{1}{4}}\left[\overline{g}_{rnf}\left(\overline{V}_{x,rnf;i} + \frac{\overline{A}_{drn;i}}{\overline{B}_{srf;i-\frac{1}{4}}\Delta x_i}\overline{V}_{x,drn;i}\right) + \overline{J}^{\prime}_{x,srf;i-\frac{1}{4}}\right] \\
& + \frac{\delta_{srm,n;i}}{\Delta x_i}\overline{G}_{srm,n}\widetilde{V}_{x,srm,n;i} + \frac{1}{\Delta x_i}\overline{G}_{grd;i}\widetilde{V}_{x,grd;i} \\
& + \frac{\delta_{int,m;i}}{\Delta x_i}\overline{G}_{int,m}\widetilde{V}_{x,int,m;i} + \frac{\delta_{dis,m;i}}{\Delta x_i}\overline{G}_{dis,m}\overline{V}_{x,dis,m} \ . \qquad (2.2)
\end{aligned}
$$

Applying the discrete-element method to the integral form of the longitudinal component of the second law of motion (along the curvilinear longitudinal *x*-axis of the main flow channel) for water contained in the downstream half-element $i + \frac{1}{4}$, the discrete-element equation for channel flow rate becomes

$$
\frac{\partial \overline{G}_{x;i+\frac{1}{4}}}{\partial t} = \frac{2}{\Delta x_i}\left(\overline{G}_{x;i}\widetilde{V}_{x;i} - \overline{G}_{x;i+\frac{1}{2}}\widetilde{V}_{x;i+\frac{1}{2}}\right) + \frac{2g_a}{\Delta x_i}\,\overline{A}_i\left(\overline{H}_i - \overline{H}_{i+\frac{1}{4}}\right) - \overline{A}_{i+\frac{1}{2}}\left(\overline{H}_{i+\frac{1}{2}} - \overline{H}_{i+\frac{1}{4}}\right)]
$$

$$
\begin{aligned}
&+ g_a \overline{A}_{i+\frac{1}{4}} \overline{\Omega}_x + \frac{2}{\Delta x_i} \left(\overline{G}^{\bullet\prime}_{x;i} - \overline{G}^{\bullet\prime}_{x;i+\frac{1}{2}} \right) + \overline{F}'_{x,bot;i+\frac{1}{4}} \\
&+ \overline{B}_{srf;i+\frac{1}{4}} \left[\overline{g}_{rnf} \left(\overline{V}_{x,rnf;i} + \frac{\overline{A}_{drn;i}}{\overline{B}_{srf;i+\frac{1}{4}} \Delta x_i} \overline{V}_{x,drn;i} \right) + \overline{J}'_{x,srf;i+\frac{1}{4}} \right] \\
&+ \frac{\delta_{srm,n;i}}{\Delta x_i} \overline{G}_{srm,n} \widetilde{V}_{x,srm,n;i} + \frac{1}{\Delta x_i} \overline{G}_{grd;i} \widetilde{V}_{x,grd;i} \\
&+ \frac{\delta_{int,m;i}}{\Delta x_i} \overline{G}_{int,m} \widetilde{V}_{x,int,m;i} + \frac{\delta_{dis,m;i}}{\Delta x_i} \overline{G}_{dis,m} \overline{V}_{x,dis,m} \qquad (2.3)
\end{aligned}
$$

The mathematical and computational characteristics of the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)] are discussed in detail in the users manual of ESTONE computer code [Eraslan (1983)].

The two sets of discrete-element equations, consisting of (1) the discrete-element equation for water surface elevation [Eq. (2.1)] and (2) the discrete-element equations for the channel flow rate [Eqs. (2.2) and (2.3)] collectively represent the fundamental hydrodynamic submodel which is common to all fast-transient, one-dimensional mathematical transport models for controlled-flow rivers and tidal estuaries of all the topical programs of the UTA project [Eraslan et al. (1976); Eraslan and Witten (1984)].

2.3.3 Discrete-Element Equation for Water Concentration of the Radionuclide in the Water Layer

The discrete-element formulation of the integral form of the pseudoconservation principle for the radionuclide in the water layer has special features which warrant special consideration. Development of the discrete-element form of this principle for the water layer (Fig. 1.1), from the standard integral form does not lead directly to the required explicit form of the discrete-element equation for water concentration of the radionuclide in the water layer. Application of the control volume integral of the pseudoconservation principle for the radionuclide [e.g., Eraslan and Diament (1984)] results in a combination of two time derivative terms: (1) the term for the time rate of change of the water concentration of the radionuclide in the water layer and (2) the term for the time rate of change of the water surface elevation. The time rate of change of water volume also contributes to the net time rate of change of the radionuclide mass (or activity) in the control volume of the element. To eliminate the term associated with the time rate of change of water surface elevation, the product of the water concentration of the radionuclide in the water layer in the element and the discrete-element equation for water surface elevation [Eq. (2.1)] is subtracted from the discrete-element form of the pseudoconservation principle for the radionuclide in the water layer in formulating the required discrete-element equation for water concentration of the radionuclide in the water layer [see Eraslan and Diament (1984) for the detailed derivation of this equation in two-dimensional, discrete-element form for general aquatic flow regions]. This new discrete-element form of the pseudoconservation principle for the radionuclide in the water layer is uniquely different from the conventional conservative and nonconservative discretized computational forms of the pseudoconservation principle for the radionuclide [e.g., U.S. Nuclear Regulatory Commission (1977), White and Eckerman (1982)]; and it can be classified as a new, discretized, "intensive" form of the pseudoconservation principle for the radionuclide in the water layer for the solution of the water concentration conditions of the radionuclide in the water layer in a controlled-flow river or a tidal estuary.

The final computational form of the discrete-element equation for the water concentration of the radionuclide in the water layer in element *i* becomes

$$\begin{aligned}
\frac{\partial \overline{C}_{rw;i}}{\partial t} = {} & \overline{C}_{rw;i} + \frac{1}{\Delta x_i \overline{A}_i}[\overline{G}_{x;i-½}(\overline{C}_{rw;i-½} - \overline{C}_{rw;i}) - \overline{G}_{x;i+½}(\overline{C}_{rw;i+½} - \overline{C}_{rw;i})] \\
& + \frac{1}{\Delta x_i \overline{A}_i}[\overline{G}_{rw,x;i-½} - \overline{G}_{rw,x;i+½}] + \frac{1}{\Delta x_i \overline{A}_i}\overline{G}_{grd,wl;i}(\overline{C}_{rw,grd,wl;i} - \overline{C}_{rw;i}) \\
& + \frac{1}{\Delta x_i \overline{A}_i}\overline{G}_{rw,bot;i} + \frac{B_{srf;i}}{\overline{A}_i}\overline{g}_{rnf}[(\overline{C}_{rw,rnf} - \overline{C}_{rw;i}) + \frac{\overline{A}_{drn;i}}{\Delta x_i \overline{B}_{srf;i}}(\overline{C}_{rw,drn;i} - \overline{C}_{rw;i})] \\
& + \frac{\delta_{srm,n;i}}{\Delta x_i \overline{A}_i}\overline{G}_{srm,n,wl;i}(\overline{C}_{rw,srm,n,wl;i} - \overline{C}_{rw;i}) + \frac{\delta_{int,m;i}}{\Delta x_i \overline{A}_i}\overline{G}_{int,m,wl;i}(\overline{C}_{rw,int,m,wl;i} - \overline{C}_{rw;i}) \\
& + \frac{\delta_{dis,m;i}}{\Delta x_i \overline{A}_i}\overline{G}_{dis,m,wl;i}(\overline{C}_{rw,dis,m,wl;i} - \overline{C}_{rw;i}) \ . \qquad (2.4)
\end{aligned}$$

The left side of Eq. (2.4) represents the net time rate of change of the water concentration of the radionuclide in the water layer in element *i*, and it is equal to the cumulative effect of the eight terms on the right side of Eq. (2.4). Each term on the right side of Eq. (2.4) corresponds to the individual contribution of a physical phenomenon that can control the time rate of change of the water concentration (depth-averaged) of the radionuclide in the water layer in element *i*. The eight terms represent the following:

1. Net convective radionuclide transport effect, representing the net difference in convective radionuclide transport rates (along the curvilinear longitudinal *x*-axis of the main flow channel), consisting of the modified inflow convective radionuclide transport rate (consistent with the intensive form) at the upstream enclosure surface at *i* − ½ and the modified outflow convective radionuclide transport rate (consistent with the intensive form) at the downstream enclosure surface at *i* + ½ in the water layer in element *i*, as

$$[\overline{F}_{cnv}(\overline{C}_{rw})]_i = \frac{1}{\Delta x_i \overline{A}_i}[\overline{G}_{x;i-½}(\overline{C}_{rw;i-½} - \overline{C}_{rw;i}) - \overline{G}_{x;i+½}(\overline{C}_{rw;i+½} - \overline{C}_{rw;i})] \ . \qquad (2.5)$$

2. Net nonconvective radionuclide transport effect, representing the net difference in nonconvective radionuclide transport rates (along the curvilinear longitudinal *x*-axis of the main flow channel), consisting of the nonconvective radionuclide transport rate (as the combination of the molecular radionuclide transport rate, convection-defect radionuclide transport rate and eddy-turbulent radionuclide transport rate) at the upstream enclosure surface at *i* − ½ and the nonconvective radionuclide transport rate (as the combination of the molecular radionuclide transport rate, convection-defect radionuclide transport rate and eddy-turbulent radionuclide transport rate) at the downstream enclosure surface at *i* + ½ in the water layer in element *i*, as

$$[\overline{F}_{trb}(\overline{C}_{rw})]_i = \frac{1}{\Delta x_i \overline{A}_i} [\overline{G}_{rw,x;i-\frac{1}{2}} - \overline{G}_{rw,x;i+\frac{1}{2}}] \ . \tag{2.6}$$

3. Effect of the convective radionuclide transport associated with the groundwater seepage flow into or out of the main flow channel in the water layer in element *i*, as

$$[\overline{F}_{grd}(\overline{C}_{rw})]_i = \frac{1}{\Delta x_i \overline{A}_i} \overline{G}_{grd,wl;i}(\overline{C}_{rw,grd,wl;i} - \overline{C}_{rw;i}) \ . \tag{2.7}$$

4. Net bottom radionuclide transport effect at the bottom of the water layer in element *i*, associated with all the phenomena that can contribute to the transport of the radionuclide between the water layer and the bottom layer in element *i*, as

$$[\overline{F}_{bot}(\overline{C}_{rw})]_i = \frac{1}{\Delta x_i \overline{A}_i} \overline{G}_{rw,bot;i} \ . \tag{2.8}$$

5. Net effect of radionuclide transport associated with the rainfall in the geographic (climatological) region of the main flow channel, including the direct radionuclide transport rate into the main flow channel, resulting from the rainfall on the water surface and the indirect radionuclide transport rate into the main flow channel, resulting from the drainage in flow rate, controlled by the rainfall rate and the radionuclide concentration conditions on the drainage areas in the geographical region, in the water layer in element *i*, as

$$[\overline{F}_{srf}(\overline{C}_{rw})]_i = \frac{\overline{B}_{srf;i}}{\overline{A}_i} \bar{g}_{rnf} [(\overline{C}_{rw,rnf} - \overline{C}_{rw;i}) + \frac{\overline{A}_{drn;i}}{\Delta x_i \overline{B}_{srfi;}} (\overline{C}_{rw,drn;i} - \overline{C}_{rw;i})] \ . \tag{2.9}$$

6. Effect of convective radionuclide transport rate associated with the flow of stream or tributary *n*, into or out of the main flow channel in the water layer in element *i*, as

$$[\overline{F}_{srm}(\overline{C}_{rw})]_i = \frac{\delta_{srm,n;i}}{\Delta x_i \overline{A}_i} \overline{G}_{srm,n,wl;i}(\overline{C}_{rw,srm,n,wl;i} - \overline{C}_{rw;i}) \ . \tag{2.10}$$

7. Net convective radionuclide transport effect associated with the intake flow rate and discharge flow rate of plant *m* into and/or out of the main flow channel in the water layer in element *i*, as

$$\begin{aligned} [\overline{F}_{plt}(\overline{C}_{rw})]_i = {} & \frac{\delta_{int,m;i}}{\Delta x_i \overline{A}_i} \overline{G}_{int,m,wl;i}(\overline{C}_{rw,int,m,wl;i} - \overline{C}_{rw;i}) \\ & + \frac{\delta_{dis,m;i}}{\Delta x_i \overline{A}_i} \overline{G}_{dis,m,wl;i}(\overline{C}_{rw,dis,m,wl;i} - \overline{C}_{rw;i}) \ . \end{aligned} \tag{2.11}$$

8. Radiological decay effect of the radionuclide in the water layer in element *i*, as

$$[\overline{F}_{rad}(\overline{C}_{rw})]_i = \overline{C}_{rw;i} \ . \tag{2.12}$$

Hence, the discrete-element equation for the water concentration of the radionuclide in the water layer in element *i* [Eq. (2.4)] represents the time rate of change of the water concentration of the radionuclide in the water layer in the element *i* as being equal to the right-side solution function for water concentration of the radionuclide in the water layer $[\overline{F}_{wl}(C_{rw})]_i$ in element *i*, which consists of the sum of eight terms, each representing the individual contribution of a different physical phenomenon, associated with radionuclide transport, that can control the time rate of change of the water concentration of the radionuclide in the water layer in element *i*, as

$$\frac{\partial \overline{C}_{rw;i}}{\partial t} = [\overline{F}_{wl}(\overline{C}_{rw})]_i = [\overline{F}_{cnv}(\overline{C}_{rw})]_i + [\overline{F}_{trb}(\overline{C}_{rw})]_i + [\overline{F}_{grd}(\overline{C}_{rw})]_i + [\overline{F}_{bot}(\overline{C}_{rw})]_i$$

$$+ [\overline{F}_{srf}(\overline{C}_{rw})]_i + [\overline{F}_{srm}(\overline{C}_{rw})]_i + [F_{plt}(\overline{C}_{rw})]_i + [\overline{F}_{rad}(\overline{C}_{rw})]_i \ . \qquad (2.13)$$

The discrete-element equations for water concentration of the radionuclide in the water layer [Eqs. (2.4) and (2.13)] possess certain properties associated with the mathematical formulation of its convective radionuclide transport terms [Eq. (2.5)] that are distinctly different from the ones associated with the discretized formulations of the conventional, conservative form of the pseudoconservation principle for the radionuclide. Considering only the convective radionuclide transport terms, the present discrete-element formulation of the pseudoconservation principle for the radionuclide in the water layer in element *i* can be stated as

$$\frac{\partial \overline{C}_{rw;i}}{\partial t} = \frac{1}{\Delta x_i \overline{A}_i} [\overline{G}_{x;i-½}(\overline{C}_{rw;i-½} - \overline{C}_{rw;i})$$

$$- \overline{G}_{x;i+½}(\overline{C}_{rw;i+½} - \overline{C}_{rw;i})] + (\text{other terms}) \ . \qquad (2.14)$$

Similarly, considering only the convective radionuclide transport terms, a corresponding form of the conventional conservative form of the equation for water concentration of the radionuclide in the water layer in element *i*, which is equivalent to the finite-difference form of spatial discretization of the pseudoconservation principle for the radionuclide, can be represented as

$$\frac{\partial}{\partial t} (\Delta x_i \overline{A}_i \overline{C}_{rw;i}) = \overline{G}_{x;i-½} \overline{C}_{rw;i-½} - \overline{G}_{x;i+½} \overline{C}_{rw;i+½} + (\text{other terms}) \ . \qquad (2.15)$$

The left side of Eq. (2.15) is the net time rate of change of the total amount of radionuclide mass (activity) in the volume of element *i*, which represents the time rate of change of an "extensive" quantity associated with the volume of the element *i* as $(\Delta x_i \overline{A}_i)$. Furthermore, the convective radionuclide transport terms on the right side of Eq. (2.15) represent the total amounts of convective radionuclide transport rates associated with the inflow rate at the upstream enclosure surface at *i* − ½ and with the outflow rate at the downstream enclosure surface at *i* + ½ in element *i*. Since each convective radionuclide transport term in Eq. (2.15) consists of the product of the flow rate and the water concentration of the radionuclide in the water layer associated with the flow rate, each convective radionuclide transport term represents the total amount of radionuclide mass (activity) transport rate with the volumetric flow rate; and therefore, it also represents an extensive quantity. Hence, for general, transient, nonuniform flow conditions, Eq. (2.15) cannot be used directly for the solution of the water concentration of the radionuclide in the water layer in element *i*, because the integration of Eq. (2.15) results in the solution for the total amount of radionuclide mass (activity) in the water layer in element *i*, which is an extensive quantity. To obtain the solution for the water concentration of the radionuclide in the water layer in element *i*, it is necessary to obtain the volume of the water mixture in the element i which requires the solution of the discretized equation for the conservation principle for the mass of the water mixture. The solution of water concentration of the radionuclide in the water layer in element i subsequently can be obtained by dividing the total amount of radionuclide mass (activity) in the water layer in element i by the volume of the water mixture in the water layer in element i. Hence, in mathematical formulations that use the conventional conservative form of the discretized equation for the pseudoconservation principle for the radionuclide in the water layer in element i [Eq. (2.15)], the solution for water concentration of the radionuclide in the water layer in element i, which is strictly an intensive quantity because it represents the radionuclide mass (activity) per unit volume (or per unit mass for constant mass density) of water mixture, requires the solution of the volume of the water mixture in the water layer in element i and the total amount of radionuclide mass (activity) in the water layer in element i, both of which are extensive quantities. Consequently, in mathematical formulations that use the conventional conservative form of the discretized equation for the pseudoconservation principle for the radionuclide in the water in element i [Eq. (2.15)], the solution of the water concentration of the radionuclide in the water layer in element i is directly and strongly affected by the computational errors that can be introduced during the solution of the equation for the conservation principle for the mass of water mixture in the water layer in element i.

On the other hand, the left side of the present discrete-element equation for water concentration of the radionuclide in the water layer [Eqs. (2.4) and (2.14)] is the time rate of change of the water concentration of the radionuclide in the water layer in element i, which is the time rate of change of a strictly intensive quantity that represents the radionuclide mass (activity) per unit volume (or per unit mass for constant mass density) of the water mixture in the water layer in element i. Furthermore, the convective radionuclide transport terms on the right side of Eq. (2.4) or (2.14) represent the net difference in convective radionuclide transport rates, consisting of (1) the corrective inflow convective radionuclide transport rate, which results solely from the difference between the water concentration of the radionuclide in the water layer of the water mixture of the inflow rate at the upstream enclosure surface at $i - ½$ and the water concentration of the radionuclide in the water layer in element i, and (2) the corrective outflow convective radionuclide transport rate, which results solely from the difference between the water concentration of the radionuclide in the water layer of the water mixture of the outflow rate at the downstream enclosure surface at $i + ½$ and the water concentration of the radionuclide in the water layer in element i. Since each convective radionuclide transport term in Eq. (2.4) or (2.14) includes the flow rate divided by the volume $(\Delta x_i \overline{A}_i)$ of the element i and consists of the product of the flow rate divided by the volume of the element and the difference between the water concentration of the radionuclide in the water layer of either the inflow rate or outflow rate of the water mixture and the water concentration of the radionuclide in the water layer in element i, each convective radionuclide transport rate is based strictly on the "relative intensive" quantity being the "water concentration difference" of the radionuclide in the water layer. Hence, for general flow conditions, including steady, uniform flow conditions and transient, nonuniform flow conditions in the main flow channel, Eq. (2.4) or (2.14) can be utilized directly for the solution of the water concentration of the radionuclide in the water layer in element i. Furthermore, since the present discrete-element formulation does not directly require the simultaneous solution of the discretized equation for the conservation principle for the mass of water mixture, in contrast to the mathematical formulations that utilize the conventional conservative form of the discretized pseudoconservation principle for the radionuclide in the water layer in element i [Eq. (2.15)], the solution of the water concentration of the radionuclide in the water layer in element i from the solution of the present discrete-element form of the pseudoconservation principle for the radionuclide in the water layer [Eq. (2.4) or (2.14)] cannot be directly affected by the computational errors introduced in the solution of the flow conditions based on the solution of the equation for the conservation principle for the mass of water mixture in the water layer in element *i*.

Hence, this new discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)], which represents the discrete-element form of the pseudoconservation principle for the radionuclide in the water layer in element *i*, is uniquely different from all other conventional, conservative, discretized forms of the pseudoconservation principle for the radionuclide in the water layer. Therefore, it can be classified as a new, discretized intensive form of discrete-element equation for the water concentration of the radionuclide that can be used directly for the solution of the intensive quantity, water concentration of the radionuclide in the water layer of the main flow channel.

A typical problem that illustrates the superior computational properties of the present discrete-element intensive form of the equation for water concentration of the radionuclide in the water layer [Eq. (2.4)] in comparison with the computational properties of the conventional conservative forms of the discretized equations for the pseudoconservation principle for the radionuclide in the water layer [Eq. (2.15)] is frequently encountered in simulating water concentrations conditions of the radionuclide in the water layer of a main flow channel having fast-transient and spatially nonuniform flow conditions, but also having initially uniform (generally zero concentration) conditions for the water concentration of the radionuclide in the water layer either over relatively long parts or over the entire longitudinal length of the main flow channel. Application of only the convective radionuclide transport parts of the mathematical models that utilize the conventional conservative forms of the equation for water concentration of the radionuclide in the water layer [Eq. (2.15)] for the simulation of the water concentration conditions of the radionuclide in the water layer in a main flow channel, having fast-transient and spatially nonuniform flow conditions, generally produces unrealistic, temporally oscillating and spatially nonuniform water concentration conditions of the radionuclide in the water layer in the elements which should remain unaffected, as the cumulative result of the direct effects of the computational errors introduced in the solution of the local, flow conditions in the main flow channel. These oscillating and nonuniform variational characteristics of the solutions of water concentration of the radionuclide in the water layer in the elements, which should remain unaffected, result in accumulated errors in long-term numerical integration; and, therefore, they can cause substantial errors in the simulation of the water concentration conditions of the radionuclide in the water layer of the main flow channel. However, the application of only the convective radionuclide transport part of the present discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)] can produce correct and realistic simulation of the water concentrations conditions of the radionuclide in the water layer, which remain steady and uniform in all the elements which should remain unaffected, because the special intensive form of the convective radionuclide transport terms on the right side of Eq. (2.4) or (2.14) become identically zero for spatially uniform water concentration conditions of the radionuclide in the water layer, regardless of the temporal and/or spatial variation of the flow conditions included in the representations of the inflow rate of the upstream enclosure surface at $i - ½$ and outflow rate at the downstream enclosure surface at $i + ½$ of the elements which should remain unaffected.

The computational algorithm of the transient, one-dimensional, two-layer radionuclide transport model and its associated computer code RADONE simultaneously solves for the water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in all the elements $i = 1, \ldots, N$, by numerically integrating the intensive form of the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)].

2.3.4 Discrete-Element Equation for Bottom Concentration of the Radionuclide in the Bottom Layer

According to the conceptual development of the fast-transient, one-dimensional, two-layer radionuclide transport model (Sect. 1.3), the overall effect of the radionuclide transport along the curvilinear longitudinal x-axis in the bottom layer is negligible in comparison to the overall effect of radionuclide transport along the vertical direction between the water layer and the bottom layer in the main flow channel. Furthermore, without any loss of generality in the formulation of the fast-transient, one-dimensional, two-layer radionuclide transport model, the depth of the bottom layer D_{bl} is assumed as a specified constant throughout the main flow channel, provided that the specified depth of the bottom layer D_{bl} is sufficiently smaller than the depth of the main flow channel $\overline{D}$, which represents the depth of the water layer.

Considering a similar procedure used in the development of the intensive form of the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)], the final computational form of the discrete-element equation for the bottom concentration of the radionuclide in the bottom layer in element i becomes

$$\frac{\partial \overline{C}_{rb;i}}{\partial t} = \overline{C}_{rb;i} + \frac{1}{\Delta x_i \Gamma_i D_{bl}} \overline{G}_{grd,bl;i} (\overline{C}_{rb,grd,bl;i} - \overline{C}_{rb;i}) + \frac{1}{\Delta x_i \Gamma_i D_{bl}} \overline{G}_{rb,bot;i}$$

$$+ \frac{\delta_{srm,n;i}}{\Delta x_i \Gamma_i D_{bl}} \overline{G}_{srm,n,bl;i} (\overline{C}_{rb,srm,n,bl;i} - \overline{C}_{rb;i}) + \frac{\delta_{int,m;i}}{\Delta x_i \Gamma_i D_{bl}} \overline{G}_{int,m,bl;i} (\overline{C}_{rb,int,m,bl;i} - \overline{C}_{rb;i})$$

$$+ \frac{\delta_{dis,m;i}}{\Delta x_i \Gamma_i D_{bl}} \overline{G}_{dis,m,bl;i} (\overline{C}_{rb,dis,m,bl;i} - \overline{C}_{rb;i}) \ . \tag{2.16}$$

The left side of Eq. (2.16) represents the net time rate of change of the bottom concentration of the radionuclide in the bottom layer in element i; and it is equal to the cumulative effect of the five terms on the right side of Eq. (2.16). Each term on the right side of Eq. (2.16) corresponds to the individual contribution of a physical phenomenon that can control the time rate of change of the bottom concentration of the radionuclide in the bottom layer in element i. The five terms represent the following:

1. Effect of the convective radionuclide transport associated with the groundwater flow into or out of the main flow channel in the bottom layer in element i, as

$$[F_{grd}(\overline{C}_{rb})]_i = \frac{1}{\Delta x_i \Gamma_i D_{bl}} \overline{G}_{grd,bl;i} (\overline{C}_{rb,grd,bl;i} - \overline{C}_{rb;i}) \ . \tag{2.17}$$

2. Net bottom radionuclide transport effect at the top of the bottom layer in element i, associated with all the phenomena that can contribute to the transport of the radionuclide between the water layer and the bottom layer in element i, as

$$[F_{bot}(\overline{C}_{rb})]_i = \frac{1}{\Delta x_i \Gamma_i D_{bl}} \overline{G}_{rb,bot;i} \ . \tag{2.18}$$

3. Effect of convective radionuclide transport rate associated with the flow of stream or tributary n, into or out of the main flow channel in the bottom layer in element i, as

$$[\overline{F}_{srm}(\overline{C}_{rb})]_i = \frac{\delta_{srm,n;i}}{\Delta x_i \Gamma_i D_{bl}} \overline{G}_{srm,n,bl;i}(\overline{C}_{rb,srm,bl;i} - \overline{C}_{rb;i}) \ . \tag{2.19}$$

4. Net convective radionuclide transport effect associated with the intake flow rate and the discharge flow rate of plant *m* into and/or out of the main flow channel in the bottom layer in element *i*, as

$$[\overline{F}_{plt}(\overline{C}_{rb})]_i = \frac{\delta_{int,m;i}}{\Delta x_i \Gamma_i D_{bl}} \overline{G}_{int,m,bl;i}(\overline{C}_{rb,int,m,bl;i} - \overline{C}_{rb;i})$$

$$+ \frac{\delta_{dis,m;i}}{\Delta x_i \Gamma_i D_{bl}} \overline{G}_{dis,m,bl;i}(\overline{C}_{rb,dis,m,bl;i} - C_{rb;i}) \ . \tag{2.20}$$

5. Radiological decay effect of the radionuclide in the bottom layer in element *i*, as

$$[F_{rad}(\overline{C}_{rb})]_i = \overline{C}_{rb;i} \tag{2.21}$$

Hence, the discrete-element equation for bottom concentration of the radionuclide in the bottom layer in element *i* [Eq. (2.16)] represents the time rate of change of the bottom concentration of the radionuclide in the bottom layer in element *i* as being equal to the right-side solution function for bottom concentration of the radionuclide in the bottom layer $[\overline{F}_{bl}(\overline{C}_{rb})]_i$ in element *i*, which consists of the sum of five terms, each representing the individual contribution of a different physical phenomenon, associated with radionuclide transport, that can control the time rate of change of the bottom concentration of the radionuclide in the bottom layer in element *i*, as

$$\frac{\partial \overline{C}_{rb;i}}{\partial t} = [\overline{F}_{bl}(\overline{C}_{rb})]_i = [\overline{F}_{grd}(\overline{C}_{rb})]_i + [\overline{F}_{bot}(\overline{C}_{rb})]_i$$

$$+ [\overline{F}_{srm}(\overline{C}_{rb})]_i + [\overline{F}_{plt}(\overline{C}_{rb})]_i + [\overline{F}_{rad}(\overline{C}_{rb})]_i \ . \tag{2.22}$$

The discrete-element equation for bottom concentration of the radionuclide in the bottom layer in element *i* [Eq. (2.16)] again is uniquely different from all other conventional, conservative, discretized forms of the pseudoconservation principle for the radionuclide in the bottom layer. Therefore, it can also be classified as a new discretized intensive form (Sect. 2.3.3) of discrete-element equations for bottom concentration of the radionuclide that can be used directly for the solution of the intensive quantity, bottom concentration of the radionuclide in the bottom layer of the main flow channel.

The computational algorithm of the fast-transient, one-dimensional, two-layer radionuclide transport model and its associated computer code RADONE simultaneously solves for the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in all the elements $i = 1, ..., N$, by numerically integrating the intensive form of the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)].

2.4 DISCUSSION OF THE DISCRETE-ELEMENT COMPUTATIONAL SYSTEM

The governing discrete-element computational system for the solution of principal solution variables in discrete elements consists of (1) the discrete-element equation for water surface elevation $\overline{H}_i$ [Eq. (2.1)],

(2) two discrete-element equations for channel flow rates $\overline{G}_{x;i-\frac{1}{4}}$ and $\overline{G}_{x;i+\frac{1}{4}}$ [Eqs. (2.2) and (2.3)], (3) the discrete-element equation for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ [Eq. (2.4)], and (4) the discrete-element equation for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ [Eq. (2.16)].

Considering N number of specified discrete elements, the governing discrete-element computational system represents $5N$ number of first-order, moderately coupled, quasilinear, ordinary differential equations for the solution of $5N$ number of principal flow variables at three specified solution locations in discrete elements (Figs. 2.1 and 2.2). Consequently the governing discrete-element system of equations can solve for four principal flow variables, consisting of (1) water surface elevation $\overline{H}_i$, (2) channel flow rates $\overline{G}_{x;i-\frac{1}{4}}$ and $\overline{G}_{x;i+\frac{1}{4}}$, (3) water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$, and (4) bottom concentration of the radionuclide in the bottom layer, in each element at three solution locations. These locations are (1) the center of element i, (2) the center of the upstream half-element $i - \frac{1}{4}$, and (3) the center of the downstream half-element $i + \frac{1}{4}$. However, the $5N$ number of discrete-element equations also contains various additional mathematical terms that collectively render the mathematical system inconsistent because the total number of unknown variables exceeds the number of independent mathematical equations. This is consistent with the general "nonclosure" property associated with the mathematical formulations of all physical phenomena from the integral forms of conservation principles. Hence, the necessary condition for establishing a consistent mathematical system for the existence of solutions requires the elimination, in terms of values of principal solution variables at the three solution locations, of all other mathematical terms that represent:

1. values of solution variables at locations different from the solution locations,
2. nonconvective transport rates (along the direction of the curvilinear longitudinal axis x of the main flow channel), and
3. variables associated with bottom conditions, surface conditions, drainage flow conditions, stream or tributary flow conditions, groundwater seepage flow conditions, and intake and discharge flow conditions of the plants.

The establishment of the "closure" conditions of the discrete-element computational system [Eqs. (2.1), (2.2), (2.3), (2.4), and (2.16)] is presented in the subsequent sections.

3. CLOSURE OF THE DISCRETE-ELEMENT COMPUTATIONAL SYSTEM

3.1 SUMMARY DISCUSSION OF CLOSURE OF THE DISCRETE-ELEMENT COMPUTATIONAL SYSTEM

According to the mathematical development of the fast-transient, one-dimensional, two-layer radionuclide transport model, the computational algorithm of the RADONE computer code eliminates the auxiliary mathematical terms that appear in the governing discrete-element computational system [Eqs. (2.1), (2.2), (2.3), (2.4), and (2.16)] by utilizing four different methods associated with the general closure procedure of the mathematical model.

1. Auxiliary mathematical terms representing the values of a flow solution variable at the auxiliary locations different from the solution locations of the particular solution variable are eliminated on the basis of interpolation of values of the solution variable at the auxiliary locations in terms of values of the solution variable at its solution locations in the elements and/or half-elements (Sect. 3.3).
2. Auxiliary mathematical terms representing the nonconvective transport rates (along the curvilinear longitudinal x-axis of the main flow channel) at the solution and/or auxiliary locations are eliminated on the basis of formulations of nonconvective transport rates in terms of values of principal solution variables at the solution and/or auxiliary locations in the elements and/or half-elements, according to the longitudinal nonconvective transport submodel of the RADONE computer code (Sect. 3.4).
3. Auxiliary mathematical terms representing values of solution variables and nonconvective transport rates (along the curvilinear longitudinal x-axis of the main flow channel) at the auxiliary end locations of a river or an estuary are eliminated on the basis of specified end conditions (Sect. 4). The auxiliary end locations correspond to (a) the upstream-end cross section of the main flow channel at the location of the upstream enclosure surface $i - ½ = 1 - ½$ of element $i = 1$ and (b) the downstream-end cross section of the main flow channel at the location of the downstream enclosure surface $i + ½ = N + ½$ of element $i = N$.
4. Auxiliary mathematical terms associated with the conditions that affect the flow and radionuclide concentration conditions in the main flow channel, but which cannot be directly associated with longitudinal transport conditions, including (a) transport conditions at the bottom of the main flow channel, (b) transport conditions at the water surface, (c) drainage transport conditions, (d) transport conditions associated with streams and tributaries, and (e) transport conditions associated with the intakes and discharges of the plants, are eliminated based on (1) special interpolation formulations (Sect. 3.3), (2) special convective and nonconvective transport submodels (Sects. 3.5, 3.6, and 3.7), and/or (3) specified-flow transport conditions (Sect. 4).

The formulation of the general closure procedure of the fast-transient, one-dimensional, two-layer radionuclide transport model and its associated RADONE computer code includes various parts which are presented in detail in the users manual for ESTONE [Eraslan (1983)] and in the users manual for RADTWO [Eraslan and Diament (1984)]. Therefore, in the presentation of the closure of the discrete-element computational system of the fast-transient, one-dimensional, two-layer radionuclide transport model and in the discussions of the computational algorithm of its associated RADONE computer code, these common parts of the closure formulation will only be summarized, in order to eliminate the repetitive presentation of material which is common (or very similar) in three users manuals of three mathematical transport models of the Unified Transport Approach (UTA) project [Eraslan et al. (1976)].

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3.2 ADDITIONAL DEFINITIONS OF MATHEMATICAL VARIABLES ASSOCIATED WITH CLOSURE

The additional auxiliary variables used in the development of the interpolation formulas and the various transport submodels, associated with the general closure procedure of the governing discrete-element computational equations (Sect. 2) are presented in alphabetical order for the fast-transient, one-dimensional, two-layer radionuclide transport model of the RADONE computer code.

All additional auxiliary variables, associated with the general closure procedure of the mathematical model, are used for evaluating the auxiliary terms of the governing discrete-element computational equations (Sect. 2) based on the values of the solution variables at (1) common solution locations $i - ¼$, i, and $i + ¼$ in the elements and/or half-elements and (2) common auxiliary locations of the upstream and downstream enclosure surfaces at $i - ½$ and $i + ½$, respectively, of the elements and/or half-elements. Therefore, the subscripts $i - ½$, $i - ¼$, i, $i + ¼$, and $i + ½$ are omitted for convenience and brevity in subsequent definitions of the auxiliary variables. The additional auxiliary variables associated with the general closure procedure are

$C_{fr,wnd}$ = specified constant surface-wind friction coefficient associated with formulation of surface-wind stress [Eq. (3.90); suggested value is 0.0026];

$\overline{\mathcal{C}}^*_{n,D}$ = auxiliary coefficient representing one of the combined effects of the Blasius power-law-type vertical distribution of channel flow velocity and the detailed geometric properties of the cross section of the main flow channel associated with the formulation of convection-defect radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (3.50), (3.51a), and (3.51b)];

$\overline{\mathcal{C}}'_{n,D}$ = auxiliary coefficient representing the effect of detailed geometric properties of the cross section of the main flow channel according to the formulations of (1) the isotropic coefficient of eddy-turbulent transport associated with combined self-similar vertical and lateral variations of channel flow velocity and (2) combined self-similar vertical and lateral variations of water concentration of the radionuclide in the water layer in formulation of the local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport [Eqs. (3.58) and (3.60)];

$\overline{\mathcal{C}}'_{n,\beta}$ = auxiliary coefficient representing the combined effect of (1) the isotropic coefficient of eddy-turbulent transport associated with the Blasius power-law-type, self-similar vertical variation of channel flow velocity and (2) cubic, self-similar vertical variation of the water concentration of the radionuclide in the water layer in formulation of the local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport [Eqs. (3.58) and (3.69)];

$C_{rw}(y,\eta)$ = functional form for the combined self-similar vertical variation and the general lateral variation of the local water concentration of the radionuclide in the water layer [Eq. (3.33), radiologic unit/ft^3];

$\overline{\mathcal{C}}^*_{rw}(y,\eta)$ = temporally primary scale and spatially subscale part, associated with the self-similar form of the vertical and lateral variations of the water concentration of the radionuclide in the water layer [Eqs. (3.35a) and (3.35b), radiologic unit/ft^3];

$C_{rw,bot}(y)$ = local water concentration of the radionuclide in the water layer at the bottom, including the lateral variation over the cross section of the main flow channel [Eq. (3.33), radiological unit/ft^3];

$C_{rw,srf}(y)$ = local water concentration of the radionuclide in the water layer at the water surface, including the lateral variation over the cross section of the main flow channel [Eq. (3.33), radiologic unit/ft^3];

$\overline{C}'^{*}_{2,n,D}$ = auxiliary coefficient representing the effect of detailed geometric properties of the cross section of the main flow channel according to the formulation of (1) the isotropic coefficient of eddy-turbulent transport associated with combined self-similar vertical and lateral variations of channel flow velocity and (2) combined self-similar vertical and lateral variation of the water concentration of the radionuclide in the water layer in formulation of the local, cross-section-averaged secondary coefficient of eddy-turbulent radionuclide transport [Eqs. (3.62) and (3.64)];

$\overline{C}'_{2,n,\beta}$ = auxiliary coefficient representing the combined effect of (1) the isotropic coefficient of eddy-turbulent transport associated with the Blasius power-law-type, self-similar vertical variation of channel flow velocity and (2) cubic, self-similar vertical variation of the water concentration of the radionuclide in the water layer in formulation of the local, cross-section-averaged secondary coefficient of eddy-turbulent radionuclide transport [Eqs. (3.62) and (3.63)];

$\overline{D}$ = cross-section-averaged depth (averaged over the lateral surface width) of the cross section of the main flow channel (ft);

$\overline{D}_{\max}$ = maximum depth of the cross section of the main flow channel (ft);

$D(y)$ = local depth, including lateral variation over the cross section of the main flow channel (ft);

$\overline{E}''_{rw}$ = local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (3.56), (3.57), and (3.58), ft^2/h];

$\overline{E}'^{*}_{rw,2}$ = local, cross-section-averaged secondary coefficient of eddy-turbulent radionuclide transport (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (3.56), (3.61), and (3.62), ft^2/h];

f = general representative function for illustrating the formulation of the derivatives along the curvilinear longitudinal x-axis of the main flow channel [Eqs. (3.69a) through (3.70c)];

$\overline{G}_{grd,avg}$ = specified temporally constant distribution (along the curvilinear longitudinal x-axis of the main flow channel) of average groundwater seepage flow rate into or out of the main flow channel [Eq. (3.84), ft^3/h];

$\overline{G}_{grd,hwt}$ = hydrostatic groundwater seepage flow rate into or out of the main flow channel [Eq. (3.86), ft^3/h];

$\overline{G}_{grd,reg}$ = regional groundwater seepage flow rate into or out of the main flow channel [Eq. (3.84), ft^3/h];

$\overline{G}_{rw,mol,x}$ = molecular radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (3.43), (3.44), (3.47), and (3.49), radiologic unit/h];

$\overline{G}^{**}_{rw,x}$ = convection-defect radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (3.43), (3.45), (3.50), (3.51a), and (3.51b), radiologic unit/h];

$\overline{G}''_{rw,x}$ = eddy-turbulent radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (3.43), (3.46), (3.55), (3.56), (3.57) through (3.64), radiologic unit/h];

$\overline{G}_x^*$ = convection-defect momentum transport rate (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (3.41a) and (3.41b), $\mathrm{ft}^4/\mathrm{h}^2$];

$\overline{g}_{grd,hwt}$ = hydrostatic groundwater seepage flow flux into or out of the main flow channel [Eq. (3.85), ft/h];

$\overline{g}_{rb,bot}$ = net bottom radionuclide transport flux into the bottom layer, across the enclosure surface between the water layer and the bottom layer [Eq. (3.81), radiologic unit $\mathrm{ft}^{-2}\,\mathrm{h}^{-1}$];

$\overline{g}_{rw,bot}$ = net bottom radionuclide transport flux into the water layer, across the enclosure surface between the water layer and the bottom layer, as the linear combination of (1) bottom-mixing radionuclide transport flux, (2) bottom-settling radionuclide transport flux, and (3) bottom-resuspension radionuclide transport flux [Eq. (3.80), radiologic unit $\mathrm{ft}^{-2}\,\mathrm{h}^{-1}$];

$\overline{g}_{rw,turb}$ = bottom-mixing radionuclide transport flux between the water layer and the bottom layer [Eqs. (3.71), (3.72), (3.73a) through (3.73c), and (3.80), radiologic unit $\mathrm{ft}^{-2}\,\mathrm{h}^{-1}$];

$\overline{g}_{rw,fall}$ = bottom-settling (deposition) radionuclide transport flux from the water layer into the bottom layer [Eqs. (3.71), (3.74), (3.75a) through (3.75d), and (3.80), radiologic unit $\mathrm{ft}^{-2}\,\mathrm{h}^{-1}$];

$\overline{g}_{rw,susp}$ = bottom-resuspension (scouring) radionuclide transport flux from the bottom layer into the water layer [Eqs. (3.71), (3.79), and (3.80), radiologic unit $\mathrm{ft}^{-2}\,\mathrm{h}^{-1}$];

$H_{grd,hwt}$ = specified temporally varying water surface elevation of the groundwater table in the geographic (climatological) region of the main flow channel [Eq. (3.85), ft];

$H_{grd,ref}$ = specified constant reference value of the water surface elevation of the groundwater table [Eq. (3.85); arbitrarily assigned value is 2.0 ft];

$k_{rw,bot}$ = specified constant coefficient of effective vertical eddy-turbulent mixing, representing the scaling factor required for obtaining the value of the effective vertical eddy-turbulent mixing coefficient based on the value of the local isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport [Eqs. (3.72) and (3.73b)];

n = specified constant integer power of the Blasius power-law-type vertical distribution of channel flow velocity (suggested value is 8);

p_{fall} = specified constant power of the ratio of the local channel flow speed to the specified reference flow speed of settling reduction, associated with the overall inhibiting effect of the local speed of flow on the settling (deposition) rate of the lumped sediment-organic-matter class in the water layer [Eqs. (3.74) and (3.75d)];

p_{rw} = specified constant power of the ratio of the local channel flow speed to the reference channel flow speed, associated with the maximum vertical variation of the water concentration of the radionuclide in the water layer [Eqs. (3.36) and (3.37c)];

$R_{bl,grd}$ = specified constant bottom-layer groundwater distribution factor, for determining the groundwater seepage flow rate into or out of the bottom layer of the element of the main flow channel [Eq. (3.89)];

$R_{bot,turb}$ = specified constant coefficient of effective depth of vertical mixing, for representing the inverse of the part (as percent) of the local, average depth of the water layer where the effective part of the eddy-turbulent mixing in the main flow channel controls the vertical transport of the radionuclide between the water layer and the bottom layer [Eqs. (3.72) and (3.73a)];

$\overline{\mathrm{Re}}$ = Reynolds number, based on (1) the longitudinally local, cross-section-averaged depth (averaged over the lateral surface width) and (2) the longitudinally local magnitude of cross-section-averaged channel flow velocity [Eqs. (3.38a), (3.38b), and (3.39)];

$R_{grd,por}$ = specified temporally constant distribution (along the curvilinear longitudinal x-axis of the main flow channel) of the coefficient of composite ground porosity associated with the formulation of hydrostatic groundwater seepage flux into or out of the main flow channel [Eq. (3.85), ft/h];

$R_{grd,reg}$ = specified temporally varying scaling factor associated with determining the amount of regional groundwater seepage flow rate into or out of the main flow channel [Eq. (3.84)];

$R_{rb,susp}$ = specified constant coefficient of resuspension, associated with the resuspension of the settled (deposited) sediment-organic-matter class from the bottom layer into the water layer [Eq. (3.79)];

R_{rw} = specified constant parameter, associated with the maximum vertical variation of the water concentration of the radionuclide in the water layer [Eqs. (3.36) and (3.37a)];

$R_{rw,fall}$ = specified constant coefficient of effective fall speed, associated with the lumped sediment-organic-matter class in the water layer [Eqs. (3.74) and (3.75a)];

r_{grd} = specified temporally constant distribution (along the curvilinear longitudinal x-axis of the main flow channel) of the hydrostatic pressure gradient associated with the formulation of hydrostatic groundwater seepage flux into or out of the main flow channel [Eq. (3.85)];

r_{nuc} = nuclear decay rate coefficient based on the specified half-life of the radionuclide [Eqs. (3.12a), (3.12b), and (3.13), h^{-1}];

$t_{½,nuc}$ = specified half-life of the radionuclide [Eq. (3.13), h];

$V_{fr,bot}$ = bottom shear velocity, associated with the bottom drag force per unit length (along the curvilinear longitudinal x-axis of the main flow channel) which is consistent with the assumed Blasius power-law-type of vertical distribution [Eqs. (3.77a) and (3.77b), ft/h];

V_{ref} = specified constant reference value of channel flow speed associated with the reduction of the maximum vertical variation of the water concentration of the radionuclide in the water layer [Eqs. (3.36) and (3.37b), ft/h];

$V_{ref,fall}$ = specified constant reference value of channel flow speed of settling reduction, associated with the overall inhibiting effect of local speed of flow on the settling (deposition) and conditioning of the lumped sediment-organic-matter class in the water layer [Eqs. (3.74) and (3.75c), ft/h];

$V_{rb,susp}$ = critical resuspension velocity of the lumped sediment-organic-matter class, representing the threshold value of the critical resuspension velocities of all different classes of settled sediment and all different settled organic matter [Eq. (3.76), ft/h];

$V_{rw,fall}$ = specified constant effective fall velocity of the lumped sediment-organic-matter class, representing the averaged value of the fall velocities of all different classes of suspended sediment and all different suspended organic matter [Eqs. (3.74) and (3.75b), ft/h];

$\vec{V}_{wnd}$ = wind velocity vector (relative to a reference coordinate system associated with the specification of the direction of the curvilinear longitudinal x-axis of the main flow channel) in the geographic (climatological) region of the main flow channel (ft/h);

$V_x(y,\eta)$ = local channel flow velocity, including the self-similar vertical and lateral variations over the cross section of the main flow channel [Eqs. (3.31a) and (3.31b), ft/h];

$V_x^*(y,\eta)$ = temporally primary scale and spatially subscale part of the channel flow velocity, including the self-similar vertical and lateral variations over the cross section of the main flow channel [Eq. (3.31a) and (3.31b), ft/h];

$\bar{V}_{x,srf}$ = average channel flow velocity at the water surface (along the curvilinear longitudinal x-axis of the main flow channel) based on averaging the self-similar lateral variation of channel flow velocity over the width of the main flow channel [Eqs. (3.90) and (3.91), ft/h];

$\bar{V}_{x,wnd}$ = longitudinal component of wind velocity (along the curvilinear longitudinal x-axis of the main flow channel) in the geographic (climatological) region of the main flow channel [Eq. (3.90), ft/h];

y = spatially "relative" lateral coordinate of the cross section of the main flow channel normal to the curvilinear longitudinal x-axis and parallel to the water surface along the lateral direction, between the left bank (negative) and the right bank (positive), determined according to the convention of looking downstream, with the location of its origin on the water surface corresponding to the location of the maximum depth of the cross section (Fig. 3.1, ft);

z = spatially "relative" vertical coordinate (upward positive) of the cross section of the main flow channel normal to the curvilinear longitudinal x-axis and normal to the water surface, with the location of its origin corresponding to the location of the point of maximum depth of the cross section (Fig. 3.2, ft);

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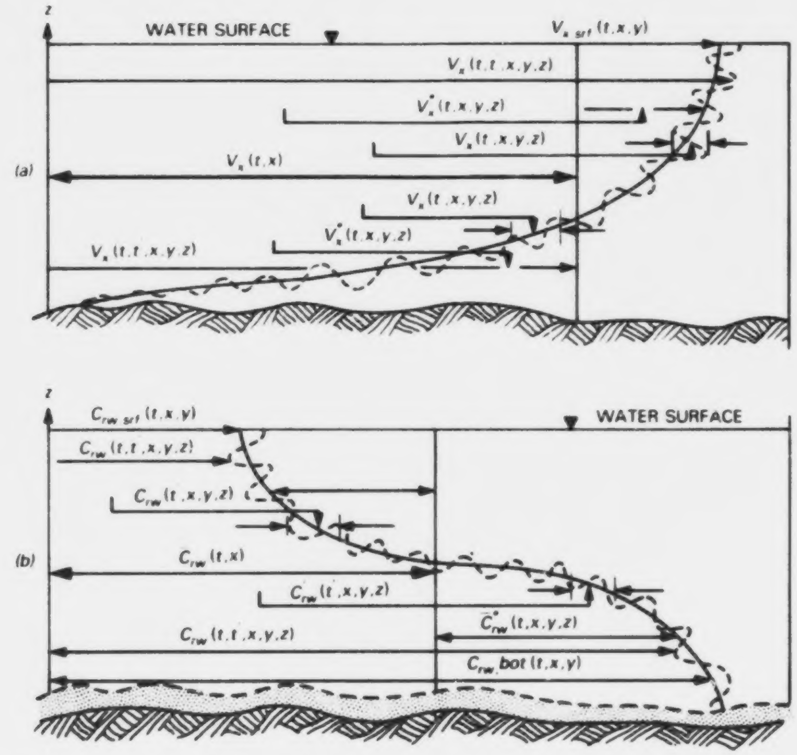
z
WATER SURFACE
$V_{x,srf}(t,x,y)$
$V_x(t,t,x,y,z)$
$V_x^*(t,x,y,z)$
$V_x(t,x,y,z)$
(a)
$V_x(t,x)$
$V_x(t,x,y,z)$
$V_x^*(t,x,y,z)$
$V_x(t,t,x,y,z)$
z
$C_{rw,srf}(t,x,y)$
WATER SURFACE
$C_{rw}(t,t,x,y,z)$
$C_{rw}(t,x,y,z)$
(b)
$C_{rw}(t,x)$
$C_{rw}(t,x,y,z)$
$\bar{C}_{rw}^*(t,x,y,z)$
$C_{rw}(t,t,x,y,z)$
$C_{rw,bot}(t,x,y)$

Fig. 3.1. Schematic representations: (*a*) channel flow velocity and (*b*) water concentration of the radionuclide in the water layer.

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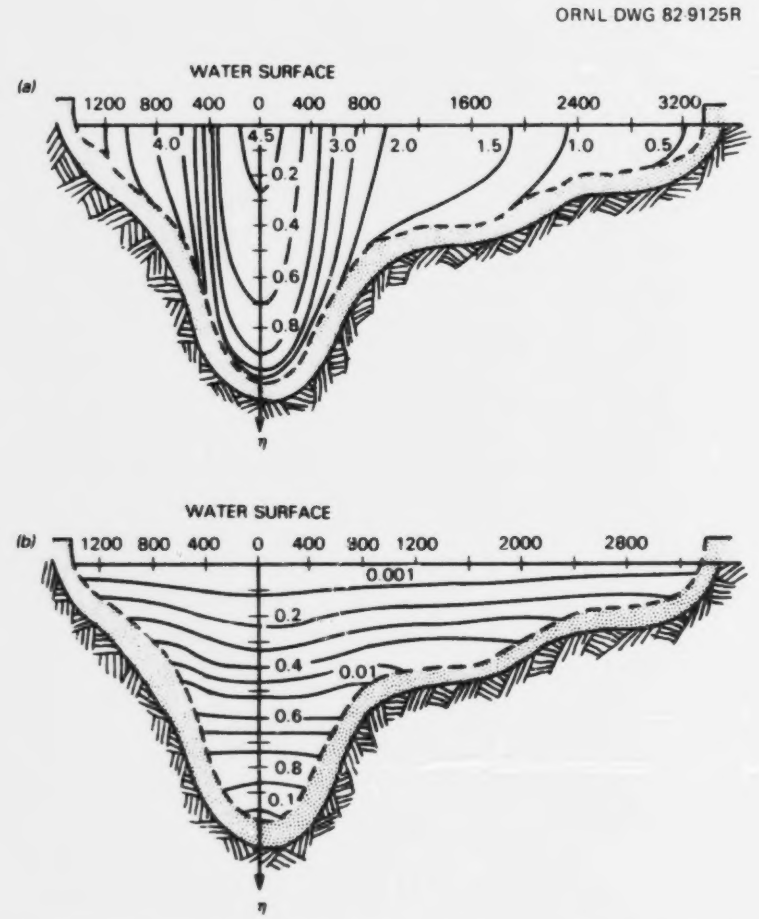
ORNL DWG 82-9125R
(a)
WATER SURFACE
1200 800 400 0 400 800 1600 2400 3200
4.5
4.0
3.0
2.0
1.5
1.0
0.5
0.2
0.4
0.6
0.8
η
(b)
WATER SURFACE
1200 800 400 0 400 800 1200 2000 2800
0.001
0.2
0.4
0.01
0.6
0.8
0.1
η

Fig. 3.2. Schematic representations: (*a*) constant velocity contours and (*b*)isoconcentration contours for water concentration of the radionuclide in the water layer.

β = specified constant bottom friction coefficient associated with formulation of the nonconvective transport model, based on the Blasius power-law-type distribution of channel flow velocity (suggested universally constant value is 0.02);

$\beta_{wnd,rnf}$ = specified constant coefficient associated with formulation of the overall effect of increasing surface-wind stress due to increasing effective density of the air-water mixture in the wind with the increasing rainfall rate per unit area in the geographic (climatological) region of the main flow channel [Eq. (3.90); suggested value is 100.0 h/ft];

$\overline{\Delta C^*_{rw,max}}$ = effective value of maximum vertical water concentration difference in the water layer, associated with the self-similar vertical variation of the water concentration of the radionuclide in the water layer [Eqs. (3.34), (3.35a), (3.35b), (3.36), (3.37a), (3.37b), and (3.37c), radiologic unit/ft^3];

$\delta_{fr,susp}$ = integer control parameter (i.e., Kronecker delta) for representing the threshold conditions associated with the bottom-resuspension radionuclide transport flux [Eq. (3.80)];

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$\epsilon(y,\eta)$ = local, isotropic coefficient of eddy-turbulent transport [Eqs. (3.54) and (3.55), ft^2/h];

$\epsilon_{bot,\min}$ = specified constant minimum bottom diffusion coefficient for evaluating the bottom-mixing radionuclide transport flux between the water layer and the bottom layer [Eqs. (3.72) and (3.73c), ft^2/h];

$\epsilon_{rw,\min}$ = specified constant minimum diffusion coefficient for radionuclide transport in the water layer, including as a part the molecular diffusion coefficient associated with molecular radionuclide transport [Eqs. (3.44), (3.47), and (3.49), ft^2/h];

$\epsilon_{rw,xx}$ = local coefficient of eddy-turbulent radionuclide transport in the water layer, the subscript xx represents the cross-sectional area being normal to the curvilinear longitudinal x-axis of the main flow channel and the transport direction being along the curvilinear longitudinal x-axis of the main flow channel [Eqs. (3.52a), (3.52b), and (3.53), ft^2/h];

η = spatially "relative," dimensionless, vertical similarity coordinate (downward positive) of the cross section of the main flow channel normal to the curvilinear longitudinal x-axis and normal to the water surface, with the location of its origin on the water surface corresponding to the location of the maximum depth of the cross section (Fig. 3.2);

ν = specified constant kinematic viscosity of mixed saline water (suggested value is 0.036 ft^2/h);

ρ_a = specified constant representing the approximate density of air (0.075 lb_m/ft^3);

$\langle\rangle$ = mathematical notation associated with the mean-integral moment of depth representing the integrated moment of depth variation along the lateral direction averaged over lateral surface width of the cross section of the main flow channel [Eqs. (3.32), (3.40), (3.42), (3.65), and (3.66), ft^p, where p is the moment of depth].

3.3 INTERPOLATION FORMULAS OF THE COMPUTATIONAL ALGORITHM

The computational algorithm of RADONE computer code solves for principal solution variables (water surface elevation $\overline{H}_i$, channel flow rates $\overline{G}_{x;i-\frac{1}{4}}$ and $\overline{G}_{x;i+\frac{1}{4}}$, water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$, and bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$) in each element at only three solution locations. These locations correspond to (1) the center of element i, (2) the center of the upstream half-element $i - \frac{1}{4}$, and (3) the center of the downstream half-element $i + \frac{1}{4}$. However, the governing discrete-element computational system [Eqs. (2.1), (2.2), (2.3), (2.4), and (2.16)] also contains values of the principal solution variables at different auxiliary locations associated with (1) the enclosure surfaces of the element, consisting of the upstream enclosure surface at $i - \frac{1}{2}$ and the downstream enclosure surface at $i + \frac{1}{2}$; (2) the enclosure surfaces of the upstream half-element, consisting of the upstream enclosure surface at $i - \frac{1}{2}$ and the downstream enclosure surface at i; and (3) the enclosure surfaces of the downstream half-element, consisting of the upstream enclosure surface at i and the downstream enclosure surface at $i + \frac{1}{2}$.

Hence, according to the requirement that the governing discrete-element computational system be mathematically consistent, values of the flow variables at the auxiliary locations must be eliminated on the basis of spatial interpolations of values of principal flow variables at the solution locations in the adjacent elements and/or half-elements. The computational algorithm of RADONE computer code utilizes three forms of interpolation formulas:

1. geometrically linear interpolation based on the curvilinear lengths (along the curvilinear longitudinal x-axis of the main flow channel) of the adjacent, arbitrarily sized elements and/or half-elements;

2. pseudospatial, second-upwind-differencing interpolation for transportive, intrinsic flow variables, according to the direction (along the curvilinear longitudinal x-axis of the main flow channel) of channel flow rate between the adjacent elements and/or half-elements;
3. generalized, nonspatial, upwind-differencing interpolation for transportive, intrinsic solution variables, according to the inflow or outflow directions of specified flow conditions associated with rainfall, drainage flows, stream or tributary flows, groundwater seepage flows, and intake and discharge flows in the element and/or half-elements.

The three different interpolation forms are used to determine values of geometric variables and principal solution variables at auxiliary locations; the interpolation forms depend on the types of geometric variables, the different types of solution variables, and their values at different solution locations in the elements and/or half-elements.

3.3.1 Interpolation of Geometric Variables

The geometric characteristics of each channel segment (along the curvilinear longitudinal x-axis of the main flow channel) are included as input data at auxiliary locations corresponding to the upstream enclosure surface at $i - ½$ and the downstream enclosure surface at $i + ½$ of element i. Input data for the geometric characteristics are based on the discretized specification of the contours of the upstream and downstream cross-sectional areas of the channel segment, which correspond to the upstream enclosure surface at $i - ½$ and the downstream enclosure surface at $i + ½$ of each element i. The computational algorithm of RADONE computer code determines all geometric characteristics at the upstream enclosure surface at $i - ½$ and the downstream enclosure surface at $i + ½$ on the basis of water surface elevation values at the auxiliary locations, which correspond to locations of the two enclosure surfaces. The geometric characteristics are determined by using specified input data in discretized form for the upstream and downstream cross-sectional contours of the channel segments (Sect. 4).

In the formulation of the discrete-element model, water surface elevation is considered as a geometric characteristic, although it is also one of the principal solution variables (Sect. 2.3.1), since it is used in the evaluation of all geometric characteristics at auxiliary locations corresponding to the locations of the upstream enclosure surface at $i - ½$ and the downstream enclosure surface at $i + ½$. Hence, interpolated values for water surface elevation at (1) the two auxiliary locations corresponding to the location of the upstream enclosure surface at $i - ½$ and the location of the downstream enclosure surface at $i + ½$ and (2) the two solution locations corresponding to the location of the upstream half-element $i - ¼$ and the location of the downstream half-element $i + ¼$ are

$$\overline{H}_{i-1/2} = \frac{(\Delta x_i \overline{H}_{i-1} + \Delta x_{i-1} \overline{H}_i)}{(\Delta x_i + \Delta x_{i-1})} \ , \tag{3.1a}$$

$$\overline{H}_{i+1/2} = \frac{(\Delta x_i \overline{H}_{i+1} + \Delta x_{i+1} \overline{H}_i)}{(\Delta x_i + \Delta x_{i+1})} \ , \tag{3.1b}$$

$$\overline{H}_{i-1/4} = \frac{1}{2}(\overline{H}_{i-1/2} + \overline{H}_i) \ , \tag{3.1c}$$

$$\overline{H}_{i+1/4} = \frac{1}{2}(\overline{H}_i + \overline{H}_{i+1/2}) \ . \tag{3.1d}$$

All geometric variables appearing in the discrete-element computational system [Eqs. (2.1), (2.2), (2.3), (2.4), and (2.16)] and in the formulation of the nonconvective transport rates (Sect. 3.4) are first evaluated at the two auxiliary locations based on already interpolated values of water surface elevation at the auxiliary locations $i - ½$ and $i + ½$ [Eqs. (3.1a) and (3.1b)]. The discretized input data for specifying the contours of the upstream cross section at $i - ½$ and the downstream cross section at $i + ½$ of the channel segment are used for the evaluation. The values of all geometric variables, including lateral surface width $\bar{B}_{srf}$ and cross-sectional area $\bar{A}$ (Sect. 3.4 for other geometric variables), at all other solution and auxiliary locations in the element and/or half-elements are determined according to the simplified form of the geometrically linear interpolation formulas based on the equal curvilinear lengths (along the curvilinear longitudinal x-axis of the main flow channel) of the upstream half-element $i - ¼$ and the downstream half-element $i + ¼$.

Hence, interpolated values for the lateral surface width $\bar{B}_{srf}$ at the three solution locations corresponding to the location of element i, the location of the upstream half-element $i - ¼$, and the location of the downstream half-element $i + ¼$ are

$$\bar{B}_{srf;i} = \frac{1}{2}(\bar{B}_{srf;i-½} + \bar{B}_{srf;i+½}) \ , \tag{3.2a}$$

$$\bar{B}_{srf;i-¼} = \frac{1}{2}(\bar{B}_{srf;i-½} + \bar{B}_{srf;i}) \ , \tag{3.2b}$$

$$\bar{B}_{srf;i+¼} = \frac{1}{2}(\bar{B}_{srf;i} + \bar{B}_{srf;i+½}) \ . \tag{3.2c}$$

Similarly, interpolated values for the cross-sectional area $\bar{A}$ at the three solution locations are

$$\bar{A}_i = \frac{1}{2}(\bar{A}_{i-½} + \bar{A}_{i+½}) \ , \tag{3.3a}$$

$$\bar{A}_{i-¼} = \frac{1}{2}(\bar{A}_{i-½} + \bar{A}_i) \ , \tag{3.3b}$$

$$\bar{A}_{i+¼} = \frac{1}{2}(\bar{A}_i + \bar{A}_{i+½}) \ . \tag{3.3c}$$

Similarly, the interpolated value for the bed contour of the main flow channel at the center solution location i is

$$\Gamma_i = \frac{1}{2}(\Gamma_{i-½} + \Gamma_{i+½}) \ . \tag{3.4}$$

The computational algorithm of RADONE computer code utilizes the geometrically linear interpolation formulas [Eqs. (3.1a) through (3.4)] at every time step of the numerical solution of the discrete-element computational system [Eqs. (2.1), (2.2), (2.3), (2.4), and (2.16)] in evaluating geometric variables at all solution locations and auxiliary locations based on the solution of water surface elevation in the three adjacent elements $i - 1$, i, and $i + 1$.

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3.3.2 Interpolation of Solution Variables Associated with Longitudinal Transport

The interpolation of solution variables associated with the longitudinal transport (along the curvilinear longitudinal x-axis of the main flow channel) uses two distinctly different methods.

The nontransportive extensive flow variable, channel flow rate $\overline{G}_x$, is interpolated directly, according to the geometrically linear interpolation formulas based on curvilinear lengths (along the curvilinear longitudinal x-axis of the main flow channel) of the adjacent elements and/or half-elements (Figs. 2.1 and 2.2). Furthermore, the auxiliary values of the transportive intrinsic solution variables, associated with nonconvective transport, but definitely not convective transport, consisting of (1) channel flow velocity $\widetilde{V}_x$ and (2) water concentration of the radionuclide in the water layer, are also interpolated directly, according to the geometrically linear interpolation formulas based on curvilinear lengths (along the curvilinear longitudinal x-axis of the main flow channel) of the adjacent elements and half-elements (Figs. 2.1 and 2.2).

However, the interpolation of the auxiliary values of the transportive intrinsic solution variables, associated with convective transport, consisting of (1) channel flow velocity $\widetilde{V}_x$ and (2) water concentration of the radionuclide in the water layer $\widetilde{C}_{rw}$, requires careful consideration of the numerical stability characteristics of the computational algorithm of the RADONE computer code. Hence, to guarantee conditional stability of the explicit numerical integration algorithm, all transportive intrinsic solution variables, associated with convective transports, are interpolated on the basis of pseudospatial, second-upwind-differencing interpolation technique, according to the direction (along the curvilinear longitudinal x-axis of the main flow channel) of the channel flow rate $\overline{G}_x$ between adjacent elements and/or half-elements.

The values of channel flow rate $\overline{G}_x$ at one solution location corresponding to the location of element i and at two auxiliary locations corresponding to the location of the upstream enclosure surface at $i - ½$ and the location of the downstream enclosure surface at $i + ½$ are interpolated from values of channel flow rate $\overline{G}_x$ at four solution locations corresponding to the locations of four adjacent half-elements $(i - 1) + ¼$, $i - ¼$, $i + ¼$, and $(i + 1) - ¼$. The geometrically linear interpolation formulas are based on the curvilinear lengths (along the curvilinear longitudinal x-axis of the main flow channel) of the adjacent half-elements as

$$\overline{G}_{x;i-½} = \frac{(\Delta x_i \overline{G}_{x;(i-1)+¼} + \Delta x_{i-1} \overline{G}_{x;i-¼})}{(\Delta x_i + \Delta x_{i-1})} \ , \tag{3.5a}$$

$$\overline{G}_{xi;} = \frac{1}{2}(\overline{G}_{x;i-¼} + \overline{G}_{x;i+¼}) \ , \tag{3.5b}$$

$$\overline{G}_{x;i+½} = \frac{(\Delta x_i \overline{G}_{x;(i+1)-¼} + \Delta x_{i+1} \overline{G}_{x;i+¼})}{(\Delta x_i + \Delta x_{i+1})} \ . \tag{3.5c}$$

Values for the intrinsic flow variable, channel flow velocity $\overline{V}_x$, at the two solution locations corresponding to the location of the upstream half-element $i - ¼$ and the location of the downstream half-element $i + ¼$ are determined on the basis of values of channel flow rate $\overline{G}_x$ and values of the cross-sectional area $\overline{A}$ at the two solution locations [Eqs. (3.3b) and (3.3c)] as

$$\overline{V}_{x;i-¼} = \frac{\overline{G}_{x;i-¼}}{\overline{A}_{i-¼}} \ , \tag{3.6a}$$

$$\overline{V}_{x;i+\frac{1}{4}} = \frac{\overline{G}_{x;i+\frac{1}{4}}}{\overline{A}_{i+\frac{1}{4}}} \quad . \tag{3.6b}$$

Similarly, the values of the transportive intrinsic solution variable, associated with nonconvective transport, but not convective transport, channel flow velocity $\overline{V}_x$, at one solution location corresponding to the location of element i (also the common enclosure surface between the two half-elements) and at two auxiliary locations, corresponding to the location of the upstream enclosure surfaces at $i - \frac{1}{2}$ and to the location of the downstream enclosure surface at $i + \frac{1}{2}$, are determined on the basis of values of channel flow rate $\overline{G}_x$ [Eqs. (3.5a), (3.5b), and (3.5c)] and the values of the cross-sectional area $\overline{A}$ [Eq. (3.3a)] at the three locations as

$$\overline{V}_{x;i-\frac{1}{2}} = \frac{\overline{G}_{x;i-\frac{1}{2}}}{\overline{A}_{i-\frac{1}{2}}} \quad , \tag{3.7a}$$

$$\overline{V}_{x;i} = \frac{\overline{G}_{x;i}}{\overline{A}_{i}} \quad , \tag{3.7b}$$

$$\overline{V}_{x;i+\frac{1}{2}} = \frac{\overline{G}_{x;i+\frac{1}{2}}}{\overline{A}_{i+\frac{1}{2}}} \quad . \tag{3.7c}$$

The values of the transportive intrinsic solution variable, associated with nonconvective transport, but not convective transport, water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, at two auxiliary locations, corresponding to the location of the upstream enclosure surface at $i - \frac{1}{2}$ and to the location of the downstream enclosure surface at $i + \frac{1}{2}$, are interpolated from the values of the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ at three solutions locations corresponding to the locations of three adjacent elements $i - 1$, i, and $i + 1$. The geometrically linear interpolation formulas are based on curvilinear lengths (along the curvilinear longitudinal x-axis of the main flow channel) of the adjacent elements as

$$\overline{C}_{rw;i-\frac{1}{2}} = \frac{\Delta x_i \overline{C}_{rw;i-1} + \Delta x_{i-1} \overline{C}_{rw;i-1})}{(\Delta x_i + \Delta x_{i-1})} \quad , \tag{3.8a}$$

$$\overline{C}_{rw;i+\frac{1}{2}} = \frac{\Delta x_i \overline{C}_{rw;i+1} + \Delta x_{i+1} \overline{C}_{rw;i})}{(\Delta x_i + \Delta x_{i+1})} \quad . \tag{3.8b}$$

The computational algorithm of RADONE computer code directly utilizes the pseudospatial, second-upwind-differencing technique [e.g., Harlow and Amsden (1970), Roache (1972), Eraslan (1974, 1975)] for the interpolation of values of all transportive intrinsic solution variables associated with the convective transport based on the already interpolated values of channel flow rate $\overline{G}_x$ [Eqs. (3.5a), (3.5b), and (3.5c)] at the upstream and/or downstream enclosure surfaces of the element and/or half-elements of the channel segment. The second-upwind-differencing technique guarantees conditional stability of the computational algorithm of the RADONE computer code, which is based on a discrete-element, explicit, multilevel, time-splitting numerical solution method. The computational algorithm does not include modifications to the standard second-upwind-differencing formulas to improve the accuracy of the interpolations by minimizing numerical errors that can lead to convergence errors in the solution (e.g., numerical dispersion).

Values of the channel flow velocity $\mathcal{V}_x$ at one solution location corresponding to the location of element i and at two auxiliary locations corresponding to the location of the upstream enclosure surface at $i - ½$ and the location of the downstream enclosure surface at $i + ½$ are interpolated from values of the channel flow velocity $\mathcal{V}_x$ at four solution locations corresponding to the locations of the four adjacent half-elements $(i - 1) + ¼$, $i - ¼$, $i + ¼$, and $(i + 1) - ¼$, according to the second-upwind-differencing interpolation, as

$$\hat{\mathcal{V}}_{x;i-½} = \mathcal{V}_{x;i-¼} \quad \text{for } \mathcal{G}_{x;i-½} \leqslant 0 \ , \tag{3.9a}$$

$$\hat{\mathcal{V}}_{x;i-½} = \mathcal{V}_{x;(i-1)+¼} \quad \text{for } \mathcal{G}_{x;i-½} > 0 \ ; \tag{3.9b}$$

$$\hat{\mathcal{V}}_{x;i} = \mathcal{V}_{x;i+¼} \quad \text{for } \mathcal{G}_{x;i} \leqslant 0 \ , \tag{3.10a}$$

$$\hat{\mathcal{V}}_{x;i} = \mathcal{V}_{x;i-¼} \quad \text{for } \mathcal{G}_{x;i} > 0 \ ; \tag{3.10b}$$

$$\hat{\mathcal{V}}_{x;i+½} = \mathcal{V}_{x;(i+1)-¼} \quad \text{for } \mathcal{G}_{x;i+½} < 0 \ , \tag{3.11a}$$

$$\hat{\mathcal{V}}_{x;i+½} = \mathcal{V}_{x;i+¼} \quad \text{for } \mathcal{G}_{x;i+½} \geqslant 0 \ . \tag{3.11b}$$

Values of water concentration of the radionuclide in the water layer $\mathcal{C}_{rw}$ at two auxiliary locations, corresponding to the location of the upstream enclosure surface at $i - ½$ and to the location of the downstream enclosure surface at $i + ½$ are interpolated from the values of the water concentration of the radionuclide in the water layer $\mathcal{C}_{rw}$ at three solution locations corresponding to the locations of three adjacent elements $i - 1$, i, $i + 1$, according to the second-upwind-differencing interpolation, as

$$\mathcal{C}_{rw;i-½} = \mathcal{C}_{rw;i} \quad \text{for } \mathcal{G}_{x;i-½} \leqslant 0 \ , \tag{3.12a}$$

$$\mathcal{C}_{rw;i-½} = \mathcal{C}_{rw;i-1} \quad \text{for } \mathcal{G}_{x;i-½} > 0 \ ; \tag{3.12b}$$

$$\mathcal{C}_{rw;i+½} = \mathcal{C}_{rw;i+1} \quad \text{for } \mathcal{G}_{x;i+½} < 0 \ , \tag{3.13a}$$

$$\mathcal{C}_{rw;i+½} = \mathcal{C}_{rw;i} \quad \text{for } \mathcal{G}_{x;i+½} \geqslant 0 \ . \tag{3.13b}$$

The computational algorithm of RADONE computer code directly utilizes the second-upwind-differencing interpolation formulas [Eqs. (3.9a) through (3.13b)] at every time step of the numerical solution of the discrete-element computational system [Eqs. (2.1), (2.2), (2.3), (2.4), and (2.16)] for evaluating the transportive intrinsic solution variables associated with convective transport at one solution location and at two auxiliary locations based on the solution of the principal solution variables in the three adjacent elements $i - 1$, i, and $i + 1$ and in the four adjacent half-elements $(i - 1) + ¼$, $i - ¼$, $i + ¼$, and $(i + 1) - ¼$.

3.3.3 Interpolation of Solution Variables Associated with Specified-Flow Transport

The computational algorithm of the RADONE computer code utilizes generalized, nonspatial, upwind-differencing interpolation forms for determining values of transportive intrinsic solution variables associated with specified-flow transport that results from (1) rainfall, (2) drainage flow, (3) stream or tributary flows, (4) groundwater seepage flow, and (5) intake and discharge flows at the plants. Values of the transportive intrinsic solution variables associated with a specified-flow transport are determined according to the specified inflow or outflow direction of the particular specified-flow condition. From strictly mathematical considerations of numerical stability, the computational algorithm of RADONE does not require the upwind-differencing form for interpolation of transportive intrinsic solution variables because numerical results of the simulations generally exhibit stable behavior for any form of specification of the intrinsic solution variables associated with specified flow conditions. However, from physical considerations, realistic representation of values of transportive intrinsic solution variables can only be formulated mathematically according to the specified inflow or outflow condition of the specified flow. The representation is based on values of transportive intrinsic solution variables of the specified flow and/or values of transportive intrinsic flow variables in the element and/or half-element associated with the particular specified flow. Furthermore, from considerations of mathematical consistency of the computational algorithm, generalized, nonspatial, upwind-differencing interpolation forms are required to establish the necessary similarity between the pseudospatial, second-upwind-differencing method of interpolation for transportive intrinsic solution variables associated with channel flow along the curvilinear longitudinal direction and the method of interpolation of transportive intrinsic flow variables associated with arbitrary directional, specified inflow or outflow conditions.

Rainfall rate per unit area $\bar{g}_{rnf}$ is specified as input data to the RADONE computer code, based on climatological conditions (Sects. 3.6 and 4.4) in the geographic region, which includes the water surface area and all drainage areas of a river or an estuary. Transportive intrinsic solution variables, consisting of velocity $\bar{V}_{x,rnf;l}$ (along the curvilinear longitudinal x-axis of the main flow channel) and the water concentration of the radionuclide in the rainfall $\bar{C}_{rw,rnf}$, associated with specified rainfall on the water surface, are either directly specified or calculated on the basis of atmospheric conditions in the geographic (climatological) region of the main flow channel as

$$\bar{V}_{x,rfn;l} = \text{specified (based on the wind speed and direction relative}$$

$$\text{to the curvilinear longitudinal } x\text{-axis of the flow channel)} \ , \tag{3.14}$$

$$\bar{C}_{rw,rnf} = \text{specified} \ . \tag{3.15}$$

RADONE computer code calculates drainage flow rate based on (1) specified input data for rainfall rate per unit area in the geographic (climatological) region and (2) specified input data for drainage areas associated with elements of channel segments along the curvilinear longitudinal x-axis of the main flow channel of a river or an estuary. Transportive intrinsic solution variables, consisting of velocity $\bar{V}_{x,drn;l}$ (along the curvilinear longitudinal x-axis of the main flow channel) and water concentration of the radionuclide $\bar{C}_{rw,drn;l}$, associated with specified drainage flow conditions from the banks of the main flow channel, are either directly specified or calculated on the basis of atmospheric and ground surface conditions in the geographic (climatological) region of the main flow channel as

$$\tilde{V}_{x,drn;i} = \text{specified (generally equal to zero, except for}$$

$$\text{simulating forced, directional drainage conditions)} \ , \tag{3.16}$$

$$\tilde{C}_{rw,drn;i} = \tilde{C}_{rw,drn} = \text{specified} \ . \tag{3.17}$$

Flow rate of each stream or tributary $\tilde{G}_{srm,n}$ into or out of the main flow channel is specified as input data to the RADONE computer code based on the available information about surface flow in the geographic region of a river or an estuary (Sect. 4). Transportive intrinsic solution variables, consisting of velocity $\tilde{V}_{x,srm,n}$ (along the curvilinear longitudinal x-axis of the main flow channel), water concentration of the radionuclide flowing into or out of the water layer $\tilde{C}_{rw,srm,n,wl}$, and bottom concentrations of the radionuclide flowing into or out of the bottom layer $\tilde{C}_{rb,srm,n,bl}$ associated with specified-flow conditions of stream or tributary n, are determined according to the generalized, nonspatial, upwind-differencing interpolation. The interpolation depends on the specified inflow or outflow direction of the specified flow rate of stream n and is based on values of transportive intrinsic solution variables of the specified stream flow and values of transportive intrinsic solution variables in the element i as

$$\tilde{V}_{x,srm,n;i} = \text{specified} \quad \text{for } \tilde{G}_{srm,n} > 0 \ , \tag{3.18a}$$

$$\tilde{V}_{x,srm,n;i} = \tilde{V}_{x,i\pm 1/2} \quad \text{for } \tilde{G}_{srm,n} \leqslant 0 \ ; \tag{3.18b}$$

$$\tilde{C}_{rw,srm,n,wl;i} = \text{specified} \quad \text{for } \tilde{G}_{srm,n} > 0 \ , \tag{3.19a}$$

$$\tilde{C}_{rw,srm,n,wl;i} = \tilde{C}_{rw,i} \quad \text{for } \tilde{G}_{srm,n} \leqslant 0 \ ; \tag{3.19b}$$

$$\tilde{C}_{rb,srm,n,bl;i} = \text{specified} \quad \text{for } \tilde{G}_{srm,n} > 0 \ , \tag{3.20a}$$

$$\tilde{C}_{rb,srm,n,bl;i} = \tilde{C}_{rb,i} \quad \text{for } \tilde{G}_{srm,n} \leqslant 0 \ . \tag{3.20b}$$

In applying RADONE computer codes, the groundwater seepage flow rate $\tilde{G}_{grd,i}$ into or out of an element of the channel segment is (1) specified as input data (Sects. 3.7 and 4.5), based on the groundwater seepage conditions of the main flow channel of a river or an estuary, or (2) calculated, based on a simple groundwater seepage model that uses available information about the approximate water table conditions in the geographic region (Sects. 3.7 and 4.5). Transportive intrinsic solution variables, consisting of velocity $\tilde{V}_{x,grd}$ (along the curvilinear longitudinal x-axis of the main flow channel), water concentration of the radionuclide flowing into or out of the water layer $\tilde{C}_{rw,grd,wl}$, and bottom concentration of the radionuclide flowing into or out of the bottom layer $\tilde{C}_{rb,grd,bl}$, associated with the specified or calculated groundwater seepage flow conditions, are determined according to generalized, nonspatial, upwind-differencing interpolation. The interpolation depends on the specified inflow or outflow direction of the specified groundwater seepage flow and is based on values of transportive intrinsic solution variables of the specified groundwater seepage flow and values of transportive intrinsic solution variables in the element i as

$$\tilde{V}_{x,grd;i} = \text{specified} \qquad \text{for } \overline{G}_{grd;i} > 0 \text{ (generally equal to zero,}$$

$$\text{except for simulating forced groundwater seepage conditions)} \;, \tag{3.21a}$$

$$\tilde{V}_{x,grd;i} = \overline{V}_{x;i \pm ¼} \qquad \text{for } G_{grd;i} \leqslant 0 \;; \tag{3.21b}$$

$$\overline{C}_{rw,grd,wl;i} = \text{specified} \qquad \text{for } \overline{G}_{grd,wl;i} > 0 \;, \tag{3.22a}$$

$$\overline{C}_{rw,grd,wl;i} = \overline{C}_{rw;i} \qquad \text{for } \overline{G}_{grd,wl;i} \leqslant 0 \;; \tag{3.22b}$$

$$\overline{C}_{rb,grd,bl;i} = \text{specified} \qquad \text{for } \overline{G}_{grd,bl;i} > 0 \;, \tag{3.23a}$$

$$\overline{C}_{rb,grd,bl;i} = \overline{C}_{rb;i} \qquad \text{for } \overline{G}_{grd,bl;i} \leqslant 0 \;. \tag{3.23b}$$

Intake flow rate $\overline{G}_{int,m}$ and discharge flow rage $\overline{G}_{dis,m}$ are specified as input data to RADONE computer code based on available information about the operational conditions of the plants (Sect. 4.7) on a river or an estuary. Furthermore, the specified input data can incorporate additional information for determining the portion of the intake flow rate withdrawn from or discharged into the water layer $\overline{G}_{int,m,wl}$, the portion of the intake flow rate withdrawn from or discharged into the bottom layer $\overline{G}_{int,m,bl}$, the portion of the discharge flow rate discharged into the water layer $\overline{G}_{dis,m,wl}$, and the portion of the discharge flow rate discharged into the bottom layer $\overline{G}_{dis,m,bl}$, based on location of the intake and discharge structures of the plant in the main flow channel (Sect. 4.7).

In formulating intake and discharge conditions of power plants, the computational algorithm of RADONF computer code considers only specified or internally determined conditions for all transportive intrinsic solution variables associated with the discharges (Sect. 4.7). However, for intake conditions, it has the user-specified option to consider various designated intakes as both intakes and discharges in the computer simulations of certain special plant operational conditions that require the intakes to operate as discharges during certain specified periods. Hence, transportive intrinsic solution variables associated with the intake flow conditions of power plant *m*, consisting of velocity $\tilde{V}_{x,int;m}$ (along the curvilinear longitudinal *x*-axis of the main flow channel), water concentration of the radionuclide withdrawn from or discharged into the water layer $\tilde{C}_{rw,int,m,wl}$, and the bottom concentration of the radionuclide withdrawn from or discharged into the bottom layer $\tilde{C}_{rb,int,m,bl}$, are determined according to generalized, nonspatial, upwind-differencing interpolation. The interpolation depends on the specified inflow or outflow directions of the specified intake flow rates and is based on values of transportive intrinsic solution variables of the specified intake and/or discharge flow rates and the values of transportive intrinsic solution variables in the element *i* as

$$\tilde{V}_{x,int,m;i} = \overline{V}_{x;i \pm ¼} \qquad \text{for } \overline{G}_{int,m} \leqslant 0 \;, \tag{3.24a}$$

$$\tilde{V}_{x,int,m;i} = \overline{V}_{x,int,m} \qquad \text{specified for } \overline{G}_{int,m} > 0$$

$$\text{(for specified intake flow as reversed discharge flow)} \;; \tag{3.24b}$$

$$\overline{C}_{rw,int,m,wl;i} = \overline{C}_{rw;i} \qquad \text{for } \overline{G}_{int,m,wl;i} \leq 0$$

$$\text{(modified according to vertical location of the intake structure)} \ , \tag{3.25a}$$

$$\overline{C}_{rw,int,m,wl;i} = \text{specified} \qquad \text{for } \overline{G}_{int,m,wl;i} > 0$$

$$\text{(for specified intake flow as reversed discharge flow)} \ ; \tag{3.25b}$$

$$\overline{C}_{rb,int,m,bl;i} = \overline{C}_{rb;i} \qquad \text{for } \overline{G}_{int,m,bl,i} \leq 0 \ , \tag{3.25c}$$

$$\overline{C}_{rb,int,m,bl;i} = \text{specified} \qquad \text{for } \overline{G}_{int,m,bl;i} > 0$$

$$\text{(for specified intake flow as reversed discharge flow)} \ . \tag{3.25d}$$

Transportive intrinsic solution variables associated with discharge flow conditions of power plant m, consisting of velocity $\overline{V}_{x,dis,m}$ (along the curvilinear longitudinal x-axis of the main flow channel), water concentration of the radionuclide discharged into the water layer $\overline{C}_{rw,dis,m,wl}$, and bottom concentration of the radionuclide discharged into the bottom layer $\overline{C}_{rb,dis,m,bl}$, are specified or internally determined on the basis of specified input data about the operational conditions and radionuclide release conditions of the plant (Sect. 4.7) in element i as

$$\overline{V}_{x,dis,m} = \text{specified} \ , \tag{3.26a}$$

$$\overline{C}_{rw,dis,m,wl;i} = \text{specified or internally determined} \ , \tag{3.26b}$$

$$\overline{C}_{rb,dis,m,bl;i} = \text{specified or internally determined} \ . \tag{3.26c}$$

In applying any advanced state-of-the-art computer code to actual site-specific problems, it is frequently impossible to find necessary input data for specifying all solution variables associated with rainfall, drainage flow, stream flow, and groundwater seepage flow conditions. Input data formats to RADONE computer code include special control parameters (integer flags) to override generalized, nonspatial, upwind-differencing interpolation forms for determining values of transportive intrinsic solution variables controlled by climatological and geologic conditions in the geographic region of a river or an estuary. User-specified input data for integer values of these control parameters can readily overcome any computational difficulty caused by the unavailability of necessary input data by considering plausible and physically realistic approximations in specifying the values of the intrinsic solution variables, consisting of velocity $\overline{V}_x$ (along the curvilinear longitudinal x-axis of the main flow channel), water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, and the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$. These values of the intrinsic solution variables are computed according to (1) user-specified input data or (2) values of the transportive intrinsic solution variables in the elements and/or half-elements of the channel segments (Sect. 4).

3.4 SUMMARY OF LONGITUDINAL NONCONVECTIVE TRANSPORT SUBMODEL

The mathematical formulation of the fast-transient, one-dimensional, two-layer radionuclide transport model of the RADONE computer code includes a longitudinal nonconvective transport submodel which is significantly different (i.e., conceptually mathematically and computationally) from conventional, longitudinally one-dimensional nonconvective transport submodels, which generally use modified formulations of turbulent transport rates based on constant or spatially varying dispersion coefficients. In the development of the longitudinal nonconvective transport submodel of the RADONE computer code, the one-dimensional application of the DEM rigorously incorporates the vertical and lateral variations of the transportive intrinsic solution variables, consisting of velocity V_x (along the curvilinear longitudinal x-axis of the main flow channel and water concentration of the radionuclide in the water layer C_{rw}, in the formulation of the longitudinally one-dimensional nonconvective transport rates along the main flow channel.

The detailed discussions of the parts of the longitudinal nonconvective transport model associated with the flow and water quality conditions are presented in the users manual for ESTONE computer code [Eraslan (1983)] for simulating fast-transient, one-dimensional, hydrodynamic, thermal, and salinity conditions in controlled rivers and tidal estuaries; and, therefore, they will not be repeated in the development of the longitudinal nonconvective transport submodel of the RADONE computer code. The discussions of the present development of the longitudinal nonconvective transport submodel of the RADONE computer code will emphasize more the parts associated with the formulation of the longitudinal nonconvective radionuclide transport rates (along the curvilinear longitudinal x-axis of the main flow channel); and it will refer the reader to the users manual for the ESTONE computer code [Eraslan (1983)] for the development of the parts associated with the longitudinal nonconvective transport rates which control the hydrodynamic conditions in the main flow channel of a controlled river or a tidal estuary.

Subsequent sections of this report summarize important mathematical aspects of the development of the longitudinal nonconvective transport submodel associated with the formulation of the nonconvective transport terms of the governing discrete-element computational system [Eqs. (2.1)–(2.4) and (2.16)].

3.4.1 Temporal and Spatial Variations of Velocity and Radionuclide Concentration Conditions

Development of the mathematical model of RADONE rigorously incorporates both vertical and lateral variations of principal solution variables over cross-sectional areas of the main flow channel in the formulations of longitudinally one-dimensional convective and nonconvective transport rates (along the curvilinear longitudinal x-axis of the main flow channel).

Considering the hierarchy of spatial scales, the assumption of longitudinally one-dimensional flow conditions requires that spatially primary-scale flow and transport phenomena be associated with variations of flow conditions along the curvilinear longitudinal x-axis of the main flow channel. Consequently in developing the one-dimensional transport model, to be consistent with the assumption about spatially primary-scale flow and transport phenomena in the water layer, the transportive intrinsic flow variables, consisting of the channel velocity V_x (along the curvilinear longitudinal x-axis of the main flow channel) and water concentration of the radionuclide in the water layer C_{rw}, must be described as averaged values over cross-sectional areas normal to the curvilinear longitudinal x-axis of the main flow channel. Furthermore, vertical and lateral variations of the transportive intrinsic flow variables over the cross-sectional areas must necessarily be considered as spatially subscale flow phenomena in the form of deviations of local flow conditions from spatially primary-scale, cross-section-averaged values of flow

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conditions in the water layer of the main flow channel (Figs. 3.1 and 3.2). Consideration of vertical and lateral variations of principal transportive intrinsic flow variables over the cross-sectional areas in the water layer, as spatially subscale flow phenomena is conceptually similar to the formulations of the convection-defect longitudinal transport rates [e.g., Eraslan (1983)] or "longitudinal dispersion transport rates" of the conventional one-dimensional transport models [e.g., Harleman (1971)] for rivers and estuaries.

Considering transient longitudinal flow conditions in a controlled river or tidal estuary, it is assumed that the temporally primary-scale flow and transport phenomena in the water layer consist of (1) uniform and/or intermittently varying flow conditions that can occur due to the operation of dams, power plants, and pump-storage facilities and (2) multiharmonic tidal flow conditions, with the dominating harmonic being the semidiurnal tide. To be consistent with these assumptions, all other high-frequency turbulence phenomena, consisting of eddies over cross-sectional areas in the water layer, must necessarily be considered temporally subscale flow phenomena, which represent deviations of instantaneous local flow conditions from temporally primary-scale flow conditions in the main flow channel. Consideration of high-frequency flow conditions, consisting of eddies over cross-sectional areas, as temporally subscale flow phenomena is again conceptually similar to consideration of high-frequency eddies as turbulent fluctuations in formulating the "turbulent transport rates" of conventional one-dimensional and multidimensional models [e.g., Pritchard (1971); Harleman (1971); Eraslan (1974, 1983); Eraslan and Diament (1984)].

The mathematical development of the transient, one-dimensional, two-layer radionuclide transport model of the RADONE computer code rigorously incorporates the effects of temporally and/or spatially subscale flow phenomena in the water layer by considering the instantaneous, local values of the principal transportive intrinsic flow variables, consisting of the channel velocity V_x (along the curvilinear longitudinal x-axis of the main flow channel) and the water concentration of the radionuclide in the water layer C_{rw}, in three parts (Fig. 3.1), according to the hierarchy of temporal and spatial scales as

$$V_x(t,t',x,y,z) = \bar{V}_x(t,x) + \bar{V}^*_x(t,x,y,z) + V'_x(t',x,y,z) \ , \tag{3.27}$$

$$C_{rw}(t,t',x,y,z) = \bar{C}_{rw}(t,x) + \bar{C}^*_{rw}(t,x,y,z) + C'_{rw}(t',x,y,z) \ . \tag{3.28}$$

where

$V_x(t,t',x,y,z)$ = instantaneous, local channel flow velocity in the water layer, including the temporally and spatially primary-scale and temporally and spatially subscale contributions, of the channel flow (long the curvilinear longitudinal x-axis of the main flow channel at the cross section of the main flow channel),

$\bar{V}_x(t,x)$ = temporally primary-scale and spatially primary-scale (i.e., temporally subscale-averaged and spatially cross-section-averaged) channel flow velocity at the cross section along the main flow channel (associated with the principal flow variable of solution channel flow rate),

$\bar{V}^*_x(t,x,y,z)$ = difference between (1) temporally primary-scale (i.e., temporally subscale-averaged), but spatially three-dimensional channel flow velocity distribution over the cross section of the main flow channel and (2) temporally primary-scale and spatially primary-scale (i.e., subscale-averaged and spatially cross-section-averaged) channel flow velocity at the cross section along the main flow channel (auxiliary flow variable associated with the formulation of all convection-defect transport rates),

$V'_x(t',x,y,z)$ = temporally subscale (i.e., high-frequency) and spatially subscale turbulent (and other eddy fluctuations) variation of channel flow velocity over the cross section of the main flow channel (auxiliary flow variables associated with the formulation of all turbulent transport rates),

$C_{rw}(t,t',x,y)$ = instantaneous, local water concentration of the radionuclide in the water layer, including the temporally and spatially primary-scale and temporally and spatially subscale contributions of the water concentration of the radionuclide in the water layer of the main flow channel,

$\overline{C}_{rw}(t,x)$ = temporally primary-scale and spatially primary-scale (i.e., temporally subscale-averaged and spatially cross-section-averaged) water concentration of the radionuclide in the water layer at the cross section of the main flow channel (principal solution variable for water concentration of the radionuclide in the water layer),

$\overline{C}^*_{rw}(t,x,y,z)$ = difference between (1) temporally primary-scale (i.e., temporally subscale-averaged), but spatially three-dimensional distribution of the water concentration of the radionuclide over the cross section of the main flow channel and (2) temporally primary-scale and spatially primary-scale (i.e., temporally subscale-averaged and spatially cross-section-averaged) water concentration of the radionuclide at the cross section of the main flow channel (auxiliary variable associated with the formulation of convection-defect radionuclide transport rate),

$C'_{rw}(t',x,y,z)$ = temporally subscale (i.e., high-frequency) and spatially subscale turbulent fluctuation (including other eddy fluctuations smaller than the size of the elements) of the water concentration of the radionuclide in the water layer (auxiliary variable associated with the formulation of the eddy-turbulent radionuclide transport rate)

The three-term formulation of instantaneous local values of the principal transportive intrinsic flow variables [Eqs. (3.27) and (3.28)] is distinctly different from the formulations used in conventional longitudinally one-dimensional radionuclide transport models for rivers and estuaries [e.g., U.S. Nuclear Regulatory Commission (1977), White and Eckerman (1982)]. The present formulation considers explicitly and rigorously every individual temporally subscale and spatially subscale part of every instantaneous local value of every principal transportive intrinsic flow variable (Fig. 3.1) in the development of the one-dimensional transport rates (along the curvilinear longitudinal *x*-axis of the main flow channel). Further detailed discussions of the consequences of the three-term formulation of instantaneous local values of the principal transportive intrinsic flow variables are presented in the users manual of the ESTONE computer code [Eraslan (1983)] and in the users manual of the RADTWO computer code [Eraslan and Diament (1984)].

3.4.2 Self-Similar Spatial Variations of Velocity and Radionuclide Concentration Conditions

Development of the mathematical model of RADONE explicitly includes the effects of spatially subscale vertical and lateral variations of principal transportive intrinsic flow variables in the formulation of temporally primary-scale and spatially primary-scale, longitudinally one-dimensional convective and nonconvective transport rates (along the curvilinear longitudinal *x*-axis of the main flow channel). According to the general formulation of DEM [e.g., Eraslan (1974, 1983); Eraslan, Lin, and Sharp (1983)], convective and nonconvective transport rates are determined by rigorously evaluating all the required surface-integral terms associated with integral forms of the four physical principles (Sect. 2) over the cross-sectional areas of the main flow channel corresponding to locations of the upstream and downstream enclosure surfaces of the elements and/or half-elements (Figs. 2.1 and 2.2). The detailed discussions of the important consequences of the formulation of the convective and nonconvective transport rates based on rigorous evaluations of the surface-integral terms are presented in the users manual of the ESTONE computer code [Eraslan (1983)].

This section presents the assumed self-similar forms of vertical and lateral variations of principal and auxiliary flow variables used in developing the nonconvective transport model of the RADONE computer code. Reasons for selecting the particular self-similar forms are discussed briefly to indicate the realistic nature of the assumed spatial variations based on considerations of flow conditions in controlled rivers and tidal estuaries. The detailed discussions of the special properties and limits of applicability of the assumed self-similar spatial variations of flow variables are also presented in the users manual of the ESTONE computer code [Eraslan (1983)], particularly for the formulations of the hydrodynamic and water quality conditions in the main flow channel of a river or an estuary.

Three-term formulations of the instantaneous local values of the principal flow variables [Eqs. (3.27) and (3.28)] are used in developing longitudinal transport rates of the one-dimensional, discrete-element model. The first of the three terms refers to temporally primary-scale and spatially primary-scale (i.e., temporally subscale-averaged and spatially cross-section-averaged) principal flow variables of the solution. The second term refers to the temporally primary-scale (i.e., temporally subscale-averaged) part associated with vertical and lateral variations of the principal flow variables over cross-sectional areas. Combined forms of the first two terms of the general three-term formulations are considered temporally primary-scale (i.e., temporally subscale-averaged), three-dimensional variations of flow variables in the main flow channel; they are separated from the third terms, which represent the temporally subscale turbulent fluctuations. These temporally subscale-averaged vertical and lateral variations of principal flow variables are formulated as self-similar forms in terms of vertical and lateral coordinates on the cross-sectional areas normal to the curvilinear longitudinal x-axis of the main flow channel, as shown in Figs. 2.1, 2.2, and 3.2.

The lateral coordinate y-axis is defined as parallel to the water surface along the lateral direction between the left bank and the right bank of the main flow channel; the location of its origin corresponds to the location of the maximum depth of the cross section (Figs. 2.1 and 3.2). The positive direction of the lateral y-axis is defined as the direction toward the right bank of the main flow channel; it is determined by looking downstream along the curvilinear longitudinal x-axis of the main flow channel. The lateral coordinate y-axis is not fixed in space; it is a spatially "relative" coordinate axis that depends on (1) orientation of the cross-sectional area with respect to the curvilinear longitudinal x-axis (Figs. 2.1 and 2.2) and (2) lateral location of the maximum depth of the cross section (Fig. 3.2). Because both the orientation and the lateral location of the maximum depth of the cross section depend on the longitudinal location of the cross section along the curvilinear longitudinal x-axis of the main flow channel, the lateral coordinate y-axis is generally different for different cross sections of the main flow channel.

The vertical coordinate η-axis is defined strictly as a similarity-type, dimensionless, independent spatial variable, as shown in Figs. 3.1 and 3.2. The variable η is also a relative coordinate axis: it depends on (1) longitudinal location and orientation of the cross-sectional area with respect to the curvilinear longitudinal x-axis of the main flow channel (Fig. 2.1) and (2) local depth of the cross section, which varies laterally along the lateral coordinate y-axis, according to the lateral profile of the bottom bed contour of the channel segment (Fig. 3.2). The vertical similarity variable η is normal to both (1) the curvilinear longitudinal x-axis of the main flow channel and (2) the lateral coordinate y-axis, which corresponds to the water surface between the banks of the cross section; it is assumed as downward positive from the water surface, along the negative direction of the vertical coordinate z-axis of the cross-sectional area of the main flow channel (Figs. 2.2, 3.1, and 3.2).

The variable η is nondimensionalized, based on local depth $D(y)$, as

$$\eta = \frac{D(y) - z}{D(y)} = 1 - \frac{z}{D(y)} \quad , \tag{3.29}$$

such that

$$\text{at} \ \ z = 0 \ , \ \eta = 1 \ , \tag{3.30a}$$

$$\text{at} \ \ z = D(y) \ , \ \eta = 0 \ . \tag{3.30b}$$

Local depth $D(y)$ in the definition of η [Eq. (3.29)] actually depends on time, because it includes water surface elevation H (relative to an arbitrarily specified level) according to solution of the principal flow variable from the discrete-element equation for water surface elevation [Eq. (2.1)].

The temporally primary-scale and spatially primary-scale nonconvective transport rates correspond to auxiliary mathematical terms of the governing discrete-element computational system [Eqs. (2.1)–(2.4)]. Hence, the temporally primary-scale, independent variable t (time) and the spatially primary-scale, independent variable x (along the curvilinear longitudinal x-axis of the main flow channel) are intentionally omitted in the presentation of the equations associated with development of the nonconvective transport model because spatially subscale variations along the lateral coordinate y-axis and the vertical z-axis of the similarity variable are more important in the development of spatially subscale, self-similar vertical and lateral variations of flow variables over the cross-sectional areas of the main flow channel. Furthermore, locations (along the curvilinear longitudinal x-axis of the main flow channel) of all self-similar variations of principal flow variables correspond to (1) the common solution locations $i - ¼$, i, and $i + ¼$ in the elements and/or half-elements and (2) common auxiliary locations of the upstream and downstream enclosure surfaces at $i - ½$ and $i + ½$, respectively, of the elements and/or half-elements. Thus, the subscripts $i - ½$, $i - ¼$, i, $i + ¼$, and $i + ½$ are omitted for convenience and brevity in subsequent presentations of spatially subscale self-similar variations of principal flow variables over the cross-sectional areas of the channel segments.

The formulation of the self-similar variation of the channel flow velocity is presented in the users manual of the ESTONE computer code [Eraslan (1983)] and, hence, will not be repeated in this section. The final form of the channel flow velocity, which includes (1) temporally primary-scale and spatially primary-scale part and (2) the temporally primary-scale and spatially subscale part, associated with self-similar variations of channel flow velocity over the cross-sectional area of the main flow channel becomes

$$V_x(y,\eta) = \bar{V}_x + \bar{V}_x^*(y,\eta) = \bar{V}_x + \bar{V}_x \left[\frac{(n+1)}{n} \, \frac{\bar{A}}{\bar{B}_{srf} \langle D^2 \rangle} D(y)(1-\eta)^{\frac{1}{n}} - 1 \right] \ , \tag{3.31a}$$

or

$$V_x(y,\eta) = \bar{V}_x + \bar{V}_x^*(y,\eta) = \bar{V}_x + \bar{V}_x \left[\frac{(n+1)}{n} \, \frac{\bar{D}}{\langle D^2 \rangle} D(y)(1-\eta)^{\frac{1}{n}} - 1 \right] \ . \tag{3.31b}$$

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The second mean-integral moment of depth $\langle D^2 \rangle$ in Eqs. (3.31a) and (3.31b) represents the integrated second moment (square power) of depth variation over the lateral surface width of the cross section:

$$\langle D^2 \rangle = \frac{1}{B_{srf}} \int_{B_{srf}} [D(y)]^2 dy \ . \qquad (3.32)$$

The assumed self-similar distribution of channel flow velocity, with variations along the lateral and vertical directions over the cross section [Eqs. (3.31a) and (3.31b)] (Fig. 3.2a), clearly illustrates the importance of the effect of detailed geometric characteristics of the cross section of the channel segment. This distribution contains the explicit term representing the second mean-integral moment of depth $\langle D^2 \rangle$ [Eq. (3.32)] of the cross section of the main flow channel. This important feature of the self-similar form of flow velocity is unique to the discrete-element formulations of the transient, one-dimensional transport models of UTA, including the present radionuclide transport model of the RADONE computer code and the mathematical models of the ESTONE computer code [Eraslan (1983)], the SEDONE computer code [Hetrick, Eraslan, and Patterson (1978)], and CHMONE computer code [Fischer et al. (1984)].

The assumed self-similar form of the combined lateral and vertical variations of channel flow velocity [Eqs. (3.31a) and (3.31b)] can be considered as only an approximate representation of velocity conditions in a river or an estuary with undirectional turbulent flow conditions in the main flow channel. The assumed self-similar form of the vertical variation of channel flow velocity cannot be considered acceptable for multilayer flow conditions with opposite directions of flow in different layers. Furthermore, the assumed self-similar form of the lateral variation of channel flow velocity cannot be considered acceptable for reversed flow conditions at different locations along the lateral direction. These locally reversed flow conditions can exist in controlled rivers and tidal estuaries with either intermittent or periodically reversing flow conditions. However, for reasonably well-mixed, turbulent flow conditions, which generally exist in a controlled river or a tidal-dominated estuary, these reversed flow conditions exist only for short durations, and they are limited mostly to small subregions along the lateral direction, between the banks of the main flow channel. Hence, the assumed self-similar form of the combined vertical and lateral variations of channel flow velocity (Fig. 3.2a) over the cross section of the main flow channel can be considered a realistic and reasonably accurate representation of actual longitudinal flow velocity conditions in a rapidly flowing, well-mixed controlled river or tidal estuary.

Vertical and lateral variations of the water concentration of the radionuclide over the cross section of the main flow channel can depend on various phenomena, including sediment transport, organic matter transport, and adsorption-desorption rates of the radionuclide associated with different classes of sediment and organic matter, which can control the local concentration conditions for the different states of the radionuclide, including the dissolved state in water, adsorbed states on different multiple classes of sediment and sorbed (adsorbed and/or absorbed) states on different organic matter in the water layer (Sect. 1.3). Considering the fundamental rationale behind the development of the transient, one-dimensional, two-layer radionuclide transport model (Sect. 1.3), it is not necessary to model precisely, and in detail, the vertical and lateral variations of the different states of the radionuclide concentration conditions in the water layer; but it is necessary to consider the important consequential effects of the vertical and lateral variations of the water concentration of the radionuclide in the water layer on the radionuclide transport rates (along the curvilinear longitudinal x-axis of the main flow channel according to the one-dimensional cross-section-averaged formulation of the general transport phenomena in the main flow channel of a river or an estuary.

Therefore, a relatively simple, but physically realistic, functional form for the combined self-similar vertical variation and the general lateral variation of the local water concentration of the radionuclide in the water layer, which satisfies the zero vertical gradient conditions at the bottom and at the water surface, can be constructed in terms of (1) the temporally primary-scale and spatially primary-scale part and (2) the temporally primary-scale and spatially subscale part, corresponding to the first two terms of the three-term formulation of the instantaneous, local water concentration of the radionuclide in the water layer [Eq. (3.28) as

$$C_{rw}(y,\eta) = C_{rw,srf}(y) + [C_{rw,bot}(y) - C_{rw,srf}(y)](3\eta^2 - 2\eta^3) \ , \tag{3.33}$$

in terms of the water concentration of the radionuclide in the water layer at the bottom $C_{rw,bot}(y)$ and the water concentration of the radionuclide in the water layer at the water surface $C_{rw,srf}(y)$, with both conditions generally varying along the lateral direction over the cross section of the main flow channel.

The lateral variation of the difference between the water concentration of the radionuclide in the water layer at the bottom $C_{rw,bot}(y)$ and the water concentration of the radionuclide in the water layer at the water surface $C_{rw,srf}(y)$ can be realistically assumed to be linearly dependent on the lateral variation of depth over the cross section, similar to the formulation of the lateral variation of the channel flow velocity over the cross section of the main flow channel. Hence, it can be formulated in terms of an effective value of maximum vertical water concentration difference $\overline{\Delta C^*_{rw,\max}}$ of the water concentration of the radionuclide in the water layer and the ratio of the local, laterally varying depth $D(y)$ to the maximum depth of the cross section of the main flow section $\overline{D}_{\max}$, such that the self-similar form of the vertical and lateral variation of the water concentration of the radionuclide in the water layer over the cross section of the main flow channel becomes

$$C_{rw}(y,\eta) = C_{rw,srf}(y) + \frac{\overline{\Delta C^*_{rw,\max}}}{\overline{D}_{\max}} D(y)(3\eta^2 - 2\eta^3) \ . \tag{3.34}$$

The water concentration of the radionuclide in the water layer at the water surface $C_{rw,srf}(y)$ can be eliminated in terms of standard geometric variables and the principal solution variable $\overline{C}_{rw}$, by integrating the self-similar form of the vertical and lateral variation of the water concentration of the radionuclide in the water layer [Eq. (3.34)] over the cross section of the main flow channel. Hence, the final form of the water concentration of the radionuclide in the water layer, which includes (1) the temporally primary-scale and spatially primary-scale part and (2) the temporally primary-scale and spatially subscale part, associated with the self-similar form of the vertical and lateral variations of the water concentration of the radionuclide in the water layer over the cross-sectional area of the main flow channel, becomes

$$\begin{aligned} C_{rw}(y,\eta) = \overline{C}_{rw} + \overline{C}^*_{rw}(y,\eta) = \overline{C}_{rw} + \frac{\Delta C^*_{rw,\max}}{2} \frac{\overline{B}_{srf}\langle D^2 \rangle}{\overline{A}\overline{D}_{\max}} \\ \times \left[1 - \frac{2\overline{A}}{\overline{B}_{srf}\langle D^2 \rangle} D(y)(3\eta^2 - 2\eta^3) \right] \ , \end{aligned} \tag{3.35a}$$

or

$$C_{rw}(y,\eta) = \overline{C}_{rw} + \overline{C}^*_{rw}(y,\eta) = \overline{C}_{rw} + \frac{\overline{\Delta C^*_{rw,\max}}}{2} \frac{\langle D^2 \rangle}{\overline{D}\overline{D}_{\max}} \left[1 - \frac{2\overline{D}}{\langle D^2 \rangle} D(y)(3\eta^2 - 2\eta^3) \right] . \tag{3.35b}$$

The assumed self-similar distribution of the water concentration of the radionuclide in the water layer, with variations along the vertical and lateral directions over the cross section [Eqs. (3.35a) and (3.35b)] (Figs. 3.1b and 3.2b), again illustrates the importance of the effect of detailed geometric characteristics of the cross section of the channel segment. This distribution also contains the explicit term representing the second mean-integral moment of depth $\langle D^2 \rangle$ [Eq. (3.32)] of the cross section of the main flow channel.

It is important to note that the self-similar form of the vertical and lateral variations of the water concentration of the radionuclide in the water layer over the cross section $C_{rw}(y,\eta)$ [Eqs. (3.35a) and (3.35b)] is precisely consistent with the definition of the cross-section-averaged water concentration of the radionuclide $\overline{C}_{rw}$, since the integral of the self-similar part representing the deviation of the water concentration of the radionuclide in the water layer from its cross-section-averaged value identically vanishes over the range of the similarity variable $0 \leqslant \eta \leqslant 1$ and over the range of the lateral coordinate y represented by the width of the water surface $\overline{B}_{srf}$ of the main flow channel.

Considering the physical phenomena that can control the vertical water concentration differences in the water layer, including vertical sediment transport, vertical organic matter transport, adsorption-desorption characteristics of the radionuclide on different classes of sediment and organic matter, and the vertical turbulent transport of the dissolved state of the radionuclide, it can be concluded that, in the overall approximate sense, the effective value of maximum vertical water concentration difference $\overline{\Delta C^*_{rw,\max}}$ depends on two local conditions at the location of a cross section of the main flow channel.

First, it is physically realistic to assume that the local effective value of maximum vertical water concentration difference $\overline{\Delta C^*_{rw,\max}}$ must depend directly on the difference between (1) the local, cross-section-averaged water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ and (2) the bottom-depth-averaged bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$. Particularly for conditions when the local bottom-depth-averaged bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$ is relatively high, corresponding to relatively high levels of contaminated bottom sediments in the main flow channel, the local effective value of maximum vertical water concentration difference $\overline{\Delta C^*_{rw,\max}}$ can be significantly large in comparison to relatively low values of cross-section-averaged water concentration of the radionuclide in the water layer, particularly if the local sediment resuspension (scouring) effects are relatively low in the main flow channel.

Second, it is physically realistic to assume that the local effective value of maximum vertical water concentration difference $\overline{\Delta C^*_{rw,\max}}$ must depend inversely on the local vertical mixing conditions, which always tend to inhibit vertical variations of all the intrinsic transportive flow variables in the main flow channel. Therefore, the local effective value of maximum vertical water concentration difference $\overline{\Delta C^*_{rw,\max}}$ must depend inversely on the local speed of the channel flow velocity in the main flow channel which effectively controls all the local vertical mixing conditions, by controlling the local bottom shear stress conditions, in the main flow channel.

Hence, based on considerations of the two fundamental local conditions associated with the local flow conditions and radionuclide concentration conditions in the main flow channel, a relatively simple, but physically realistic, functional form for the local effective value of maximum vertical water concentration difference $\overline{\Delta C^*_{rw,\max}}$ for the water concentration of the radionuclide in the water layer can be formulated as

$$\overline{\Delta C^*_{rw,\max}} = R_{rw} \; \frac{(\overline{C}_{rw} - \overline{C}_{rb})}{[1 + (|\overline{V}_x| / V_{ref})^{p_{rw}}]} \; . \tag{3.36}$$

It is important to point out that the particular three-parameter (i.e., R_w, V_{ref}, and p_{rw}) formulation of the local effective value of maximum vertical water concentration difference $\overline{\Delta C^*_{rw,\max}}$ [Eq. (3.36)] is conceptually similar to the formulations of thermal stratification and salinity stratification conditions in the main flow channel of a river or an estuary, which were used previously for simulating the hydrodynamic, water temperature, salinity, and sediment conditions in rivers and estuaries [e.g., Eraslan (1983); Hetrick, Eraslan, and Patterson (1979)].

It is also important to note that it is not essential to determine very accurate values for the three parameters, consisting of (1) coefficient for local vertical water concentration difference of the radionuclide in the water layer R_{rw}, (2) reference speed of channel flow V_{ref}, and (3) power of the ratio of the local speed of the channel flow to the reference speed of channel flow V_{ref}, in order to generate physically realistic, self-similar vertical and lateral variations of the water concentration of the radionuclide in the water layer of the main flow channel. Indeed, the ranges of the physically realistic values of the three parameters R_{rw}, V_{ref} and p_{rw} [Eq. (3.36)] can be suggested based on the results of previous studies concerned with the simulations of hydrodynamic, water-temperature, salinity, and sediment conditions in rivers and estuaries [e.g., Eraslan (1983); Hetrick, Eraslan, and Patterson (1979)], as

$$0.5 \leqslant R_{rw} \leqslant 2.0 \ , \tag{3.37a}$$

$$2.0\,\mathrm{ft/s} \leqslant V_{ref} \leqslant 4.0\,\mathrm{ft/s} \ , \tag{3.37b}$$

$$0.5 \leqslant p_{rw} \leqslant 2.0 \ . \tag{3.37c}$$

Hence, based on physical considerations, approximate self-similar vertical and lateral variations can be formulated for the principal transportive intrinsic flow variables, consisting of the channel flow velocity $V_x(y,\eta)$ [Eqs. (3.31a) and (3.31b)] and water concentration of the radionuclide in the water layer $C_{rw}(y,\eta)$ [Eqs. (3.35a) and (3.35b)], which can be used in the subsequent development of the auxiliary terms of the discrete-element computational system [Eqs. (2.1)–(2.4)] associated with the bottom drag force per unit length and all the nonconvective transport rates, along the curvilinear longitudinal x-axis of the main flow channel. The development uses these self-similar forms of vertical and lateral variations to incorporate, approximately but realistically, the important effects of the temporally primary-scale but spatially subscale vertical and lateral variations of the principal transportive intrinsic flow variables, over the cross-sectional areas of the main flow channel, in the formulation of the temporally primary-scale and spatially primary-scale longitudinally one-dimensional transport model.

3.4.3 Formulation of Bottom Drag Force in the Channel Segment

According to the general formulation of the fast-transient, one-dimensional, two-layer, discrete-element transport model of the RADONE computer code, the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)] include auxiliary terms representing bottom drag force per unit length (along the curvilinear longitudinal x-axis of the main flow channel) in the upstream and downstream half-elements corresponding to the upstream and downstream halves, respectively, of the segment of the main flow channel.

The development of the bottom drag force per unit length (along the curvilinear longitudinal x-axis of the main flow channel) is presented in the users manual for the ESTONE computer code [Eraslan (1983)] and therefore will not be repeated. The final computational form of the bottom drag force per unit length (along the curvilinear longitudinal x-axis of the main flow channel), associated with the assumed Blasius

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power-law-type, self-similar vertical distribution of channel flow velocity $V_x(y,\eta)$ [Eqs. (3.31a) and (3.31b)] becomes

$$\overline{F}'_{x,bot} = -\left\{\left[\frac{(n+1)}{n}\right]^{\frac{2n}{(n+1)}} \beta^{\frac{2n}{(n+1)}} \nu^{\frac{2}{(n+1)}}\right\}\left[\frac{\langle D^{\frac{2(n-1)}{(n+1)}}\rangle}{\overline{B}_{srf}^{\frac{(n-1)}{(n+1)}} \langle D^2\rangle^{\frac{2n}{(n+1)}}}\right]\left[\overline{G}_x^{\frac{(n-1)}{(n+1)}} \overline{G}_x\right] , \qquad (3.38a)$$

or

$$\overline{F}'_{x,bot} = -\left\{\left[\frac{(n+1)}{n}\right]^{\frac{2n}{(n+1)}} \beta^{\frac{2n}{(n+1)}} \overline{\mathrm{Re}}^{\frac{(n-1)}{(n+1)}}\right\}\left[\frac{\overline{D}^2\langle D^{\frac{2(n-1)}{(n+1)}}\rangle}{\langle D^2\rangle^{\frac{2n}{(n+1)}}}\right]\left(\overline{B}_{srf} \frac{{}_{\nu}\overline{V}_x}{\overline{D}}\right) , \qquad (3.38b)$$

where the cross-sectional Reynolds number, based on temporally primary-scale and spatially primary-scale flow variables of the longitudinally one-dimensional transport model, is defined as

$$\overline{\mathrm{Re}} = \frac{\overline{D}|\overline{V}_x|}{\nu} , \qquad (3.39)$$

and the $2(n-1)/(n+1)$ mean-integral moment of depth, representing the moment of $2(n-1)/(n+1)$ power of depth variation over the lateral surface width of the cross section of the main flow channel is defined as

$$\langle D^{\frac{2(n-1)}{(n+1)}}\rangle = \frac{1}{\overline{B}_{srf}} \int_{B_{srf}} [D(y)]^{\frac{2(n-1)}{(n+1)}} dy . \qquad (3.40)$$

The present formulation of bottom drag force per unit length $\overline{F}'_{x,bot}$ [Eqs. (3.38a) and (3.38b)] is both conceptually and computationally different from the conventional formulations of bottom drag force [e.g., Hunter (1975), Harleman (1971), Daily and Harleman (1966), Dronkers (1964), Miller (1971), Officer (1976)], which are generally based on (1) the "hydraulic radius" of the cross section and (2) the dimensional friction coefficients associated with the particular form of dependence on the hydraulic radius, as "Manning roughness factor" [e.g., Officer (1976)]. In contrast to the conventional formulations, which generally require different specified constant, or longitudinally varying, values for the bottom friction coefficients for different rivers and/or estuaries, the current formulation of bottom drag force per unit length $\overline{F}'_{x,bot}$ [Eqs. (3.38a) and (3.38b)] requires a universally constant bottom friction coefficient (with a suggested value of $\beta = 0.2$) for all rivers and estuaries with reasonably similar bottom morphological conditions in their main flow channels.

The final computational form of bottom drag force per unit length $\overline{F}'_{x,bot}$ [Eq. (3.38a)] eliminates the auxiliary terms of the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)] in terms of the principal flow variable of the solution, channel flow rate $\overline{G}_x$, and the standard geometric variables of the cross section of the main flow channel. The subscript $i - ¼$ of the auxiliary term represents bottom drag force per unit length in the upstream half-element $i - ¼$ [Eq. (2.2)]; the subscript $i + ¼$ of the auxiliary term represents bottom drag force per unit length in the downstream half-element $i + ¼$ [Eq. (2.3)]. These subscripts are not included in the general computational formulation of bottom drag force per unit length

$\overline{F}'_{x,bot}$ [Eq. (3.38a)] for convenience and brevity, because all terms on both sides of the general computational form [Eq. (3.38a)] are evaluated at the same solution locations in the upstream half-element $i - ¼$ and the downstream half-element $i + ¼$ corresponding to the upstream and downstream half-segments, respectively, of the main flow channel.

3.4.4 Formulation of Convection-Defect Momentum Transport Rate

According to the general formulation of the fast-transient, one-dimensional, two-layer, discrete-element transport model of the RADONE computer code, the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)] include auxiliary terms representing the nonconvective momentum transport rate (along the curvilinear longitudinal x-axis of the main flow channel). Each term generally consists of two parts: the convection-defect momentum transport rate and the eddy-turbulent momentum transport rate. The eddy-turbulent momentum transport rate along the longitudinal direction is generally negligible in comparison with bottom drag force, which represents the integrated shear stress, for all longitudinally one-dimensional channel flow conditions in rivers and estuaries. Hence, in the formulation of the nonconvective transport model, the nonconvective momentum transport rate can be assumed to be approximately equal to the convection-defect momentum transport rate.

The development of the nonconvective momentum transport rate (along the curvilinear longitudinal x-axis of the main flow channel) is presented in the users manual of the ESTONE computer code [Eraslan (1983)]; and, therefore, it will not be repeated. The final computational form of the nonconvective momentum transport rate (along the curvilinear longitudinal x-axis of the main flow channel, associated with the assumed Blasius power-law-type, self-similar vertical distribution of the channel flow velocity $V_x(y,\eta)$ [Eqs. (3.31a) and (3.31b)] becomes

$$\overline{G}_x^{*\prime} \simeq \overline{G}_x^{*} = -\left(1 - \left\{\left[\frac{(n+1)}{n}\right]^2 \frac{n}{(n+2)}\right\}\left[\frac{\overline{A}\langle D^3\rangle}{\overline{B}_{srf}\langle D^2\rangle^2}\right]\right)[\overline{G}_x|\overline{V}_x|] \ , \qquad (3.41a)$$

or

$$\overline{G}_x^{*\prime} \simeq \overline{G}_x^{*} = -\left(1 - \left\{\left[\frac{(n+1)}{n}\right]^2 \frac{n}{(n+2)}\right\}\left[\frac{\overline{D}\langle D^3\rangle}{\langle D^2\rangle^2}\right]\right)[\overline{G}_x|\overline{V}_x|] \ , \qquad (3.41b)$$

where the third mean-integral of depth variation over the lateral surface width of the cross section of the main flow channel is defined as

$$\langle D^3\rangle = \frac{1}{\overline{B}_{srf}} \int_{\overline{B}_{srf}} [D(y)]^3 dy \ . \qquad (3.42)$$

The present formulation, which has the leading minus sign on the right side of the convection-defect momentum transport rate $\overline{G}_x^{*}$ [Eqs. (3.41a) and (3.41b)], represents explicitly the quantitative term associated with the percentage of reduction in convective momentum transport rate that must be included in the formulation of the longitudinally one-dimensional net momentum transport rate along the curvilinear longitudinal direction of the main flow channel. The reduction is due to the temporally primary-scale and spatially subscale vertical and lateral variations of channel flow velocity $V_x(y,\eta)$ [Eqs. (3.31a) and (3.31b)] over the cross section of the main flow channel.

The explicit formulation of the nonconvective momentum transport rate, which is approximated as the convection-deflect momentum transport rate (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (3.41a) and (3.41b)] is both conceptually and computationally different from the formulations of all other longitudinally one-dimensional models for rivers and estuaries [e.g., Hunter (1975), Harleman (1971), Daily and Harleman (1966), Dronkers (1964), Miller (1971), Officer (1976)]. All other models include the overall effect of the convection-defect momentum transport in their general, and usually empirical, formulations of bottom drag force per unit length. In contrast, the present development of the nonconvective transport model rigorously formulates the explicit form of the convection-defect momentum transport rate separately from the formulation of bottom drag force per unit length.

The final computational form of the nonconvective momentum transport rate $\overline{G}_x^{*\prime}$ consisting of the convection-defect momentum transport rate G_x^* [Eq. (3.41a)] eliminates the auxiliary terms of the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)] in terms of (1) principal flow variables, channel flow rate $\overline{G}_x$, and channel flow velocity $\overline{V}_x$ and (2) standard geometric variables of the cross section of the main flow channel. All terms on both sides of the general computational form of the nonconvective momentum transport rate $\overline{G}_x^{*\prime}$ [Eq. (3.41a)] are evaluated at the same solution and/or auxiliary locations $i - ½$, i, and $i + ½$ at the locations of the upstream and downstream enclosure surfaces of the upstream half-element $i - ¼$ and/or the downstream half-element $i + ¼$ corresponding to the upstream and downstream half-segments, respectively, of the main flow channel.

3.4.5 Formulation of Nonconvective Radionuclide Transport Rate

According to the general formulation of the fast-transient, one-dimensional, two-layer, discrete-element transport model of the RADONE computer code, the discrete-element equation for the water concentration of the radionuclide in the water layer [Eq. (2.4)] includes auxiliary terms representing the nonconvective radionuclide transport rates (along the curvilinear longitudinal x-axis of the main flow channel), associated with the net nonconvective radionuclide transport effect $[F_{trb}(\overline{C}_{rw})]$ [Eq. (2.6)], each of which consists of the combination of three parts as (1) molecular radionuclide transport rate (2) convection-defect radionuclide transport rate, and (3) eddy-turbulent radionuclide transport rate, that is

$$\overline{G}_{rw,x} = \overline{G}_{rw,mol,x} + \overline{G}^{**}_{rw,x} + \overline{G}''_{rw,x} \ . \tag{3.43}$$

The general formulation of the nonconvective radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) [Eq. (3.43)] includes the contribution of the molecular radionuclide transport rate, which represents, in the correct sense, all possible radionuclide transport rates (along the curvilinear longitudinal x-axis of the main flow channel) that can occur in the absence of flow conditions which cause the convection-defect radionuclide transport effects and the eddy-turbulent radionuclide transport effects in the water layer of the main flow channel. Therefore, it is more realistic, from physical considerations, to formulate the molecular radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) as the minimum possible radionuclide transport rate as

$$\begin{aligned} \overline{G}_{rw,mol,x} &= \iint_{\overline{A}} \left[-\epsilon_{rw,\min} \frac{\partial C_{rw}}{\partial x}(t,x,y,z) \right] dA \\ &= \int_{\overline{B}_{wf}} \int_0^1 \left[-\epsilon_{rw,\min} \frac{\partial C_{rw}}{\partial x}(t,x,y,\eta) \right] D(y)\, d\eta\, dy \ . \end{aligned} \tag{3.44}$$

The convection-defect radionuclide transport rate $\overline{G}^{**}_{rw,x}$ [Eq. (3.43)] is defined according to the three-term formulations of the principal transportive intrinsic flow variables (1) channel flow velocity V_x [Eqs. (3.27), (3.31a), and (3.31b)] and (2) water concentration of the radionuclide in the water layer C_{rw} [Eqs. (3.28), (3.35a), and (3.35b)], as

$$\overline{G}^{**}_{rw,x} = \iint_{\overline{A}} V^{*}_{x}(t,x,y,z)\overline{C}^{*}_{rw}(t,x,y,z)dA = \int_{B_{wf}}\int_{0}^{1} V^{*}_{x}(y,\eta)\overline{C}^{*}_{rw}(y,\eta)D(y)d\eta dy \ . \tag{3.45}$$

The eddy-turbulent radionuclide transport rate $\overline{G}'_{rw,x}$ [Eq. (3.43)] is also defined according to the three-term formulations of the principal transportive intrinsic flow variables (1) channel flow velocity V_x [Eqs. (3.27), (3.31a), and (3.31b)] and (2) water concentration of the radionuclide in the water layer C_{rw} [Eqs. (3.28), (3.35a), and (3.35b)], as

$$\overline{G}'_{rw,x} = \iint_{A} (\overline{V'_x C'_{rw}})dA = \int_{B_{wf}}\int_{0}^{1} (\overline{V'_x C'_{rw}})D(y)d\eta dy \ . \tag{3.46}$$

Considering the simplified expression, which does not explicitly indicate the variations with time and the x coordinate along the main flow channel but which only indicates explicitly the vertical and lateral variations over the cross section of the main flow channel, the molecular radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) can be represented in an equivalent form as

$$\begin{aligned}\overline{G}_{rw,mol,x} &= \int_{B_{wf}}\int_{0}^{1}\left\{-\epsilon_{rw,min}\left[\frac{\partial\overline{C}_{rw}}{\partial x} + \frac{\partial\overline{C}^{*}_{rw}}{\partial x}(y,\eta)\right]\right\}D(y)dyd\eta \\ &= -\epsilon_{rw,min}\left[\frac{\partial\overline{C}_{rw}}{\partial x}\int_{B_{wf}}\int_{0}^{1} D(y)dyd\eta + \frac{\partial}{\partial x}\int_{B_{wf}}\int_{0}^{1}\overline{C}^{*}_{rw}(y,\eta)D(y)dyd\eta\right] \ .\end{aligned} \tag{3.47}$$

The three-term formulation of the instantaneous, local water concentration of the radionuclide in the water layer [Eq. (3.28)] guarantees that the integral over the cross-sectional area of $\overline{C}^{*}_{rw}$, which represents the difference between (1) temporally primary-scale, but spatially three-dimensional, distribution of the water concentration of the radionuclide over the cross section of the main flow channel and (2) temporally primary-scale and spatially primary-scale water concentration of the radionuclide at the cross section of the main channel, identically vanishes according to its definition; that is

$$\iint_{\overline{A}} \overline{C}^{*}_{rw}(t,x,y,z)dA = \int_{B_{wf}}\int_{0}^{1} \overline{C}^{*}_{rw}(y,\eta)D(y)dyd\eta = 0 \ . \tag{3.48}$$

Hence, considering the definition of the integral over the cross-sectional area of the main flow channel, the molecular radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) reduces to the simplified final computational form as

$$\overline{G}_{rw,mol,x} = \overline{A}\left(-\epsilon_{rw,\min}\frac{\partial\overline{C}_{rw}}{\partial x}\right) , \tag{3.49}$$

for the specified constant value of the minimum diffusion coefficient for radionuclide transport in the water layer of the main flow channel, which includes as a part the molecular diffusion coefficient associated with molecular radionuclide transport. Considering the assumed self-similar forms of the combined vertical and lateral variations of (1) channel flow velocity V_x [Eqs. (3.31a) and (3.31b)] and (2) water concentration of the radionuclide in the water layer C_{rw} [Eqs. (3.35a) and (3.35b)], the computational form of the convection-defect radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) is formulated by evaluating the integral of the general expression for the convection-defect radionuclide transport rate $\overline{G}^{**}_{rw,x}$ [Eq. (3.45)] over the cross-sectional area of the main flow channel as

$$\overline{G}^{**}_{rw,x} = (\overline{C}^{*}_{n,D}\overline{\Delta C}^{*}_{rw,\max})\overline{G}_x = \overline{A}(\overline{C}^{*}_{n,D}\overline{\Delta C}^{*}_{rw,\max}\overline{V}_x) \ , \tag{3.50}$$

where the computational form of the dimensionless coefficient $\overline{C}^{*}_{n,D}$ is

$$\overline{C}^{*}_{n,D} = \frac{\overline{B}_{srf}\langle D^2\rangle}{2\overline{A}\overline{D}_{\max}}\left[1 - \frac{12n^2}{(3n+1)(4n+1)}\frac{\overline{A}\langle D^3\rangle}{\overline{B}_{srf}\langle D^2\rangle^2}\right] , \tag{3.51a}$$

or, in a form which includes only the effect of depth variations,

$$\overline{C}^{*}_{n,D} = \frac{\langle D^2\rangle}{2\overline{D}\overline{D}_{\max}}\left[1 - \frac{12n^2}{(3n+1)(4n+1)}\frac{\overline{D}\langle D^3\rangle}{\langle D^2\rangle^2}\right] . \tag{3.51b}$$

The two product terms on the right side of the equation for convection-defect radionuclide transport rate $\overline{G}^{**}_{rw,x}$ [Eq. (3.50)] represent the following:

1. The dimensionless coefficient $\overline{C}^{*}_{n,D}$ [Eqs. (3.51a) and (3.51b)] represents the overall effect of (a) assumed vertical distributions, consisting of the Blasius power-law-type, self-similar variation for channel flow velocity and the cubic, self-similar variation for water concentration of the radionuclide in the water layer and (b) detailed geometric characteristics of the cross-sectional area associated with variable depth conditions along the lateral direction of the main flow channel. The dimensionless coefficient includes four conditions (of the cross section of the main flow channel): (a) average depth, (b) maximum depth, (c) the second mean-integral moment of depth $\langle D^2\rangle$ [Eq. (3.32)], and (d) the third mean-integral moment of depth $\langle D^3\rangle$ [Eq. (3.42)].
2. The dimensional product term $(\overline{A\Delta C^{*}_{rw,\max}V_x})$ represents the maximum possible convection-defect radionuclide transient rate (along the curvilinear longitudinal x-axis of the main flow channel) that can occur under flow conditions which determine the effective value of maximum vertical water concentration difference $\overline{\Delta C}^{*}_{rw,\max}$ [Eqs. (3.34) and (3.36)] over the cross section of the main flow channel.

The present formulation of the convection-defect radionuclide transport rate $\overline{G}^{**}_{rw,x}$ [Eqs. (3.50), (3.51a), and (3.51b)] represents explicitly the quantitative term associated with the additional radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) that must be included in the formulation of the one-dimensional, net radionuclide transport rate, along the curvilinear longitudinal direction, in the water layer of the main flow channel. This additional radionuclide transport rate in the water layer is due to the temporally primary-scale and spatially subscale vertical and lateral variations of the channel flow velocity V_x [Eqs. (3.27), (3.31a), and (3.31b)] and the temporally primary-scale and spatially subscale vertical and lateral variations of the water concentration of the radionuclide in the water layer C_{rw} [Eqs. (3.28), (3.35a), and (3.35b)] over the cross section of the main flow channel. Hence, the convection-defect radionuclide transport rate $\overline{G}^{**}_{rw,x}$ [Eqs. (3.50), (3.51a), and (3.51b)] represents explicitly the longitudinal radionuclide transport rate in the water layer associated, in a sense, with the "dispersion phenomenon," based on assumed approximate, self-similar forms of combined vertical and lateral variations of the channel flow velocity V_x [Eqs. (3.27), (3.31a), and (3.31b)] and the water concentration of the radionuclide in the water layer C_{rw} [Eqs. (3.28), (3.35a), and (3.35b)], without requiring any additional information about the effect of the longitudinal dispersion along the main flow channel of a river or an estuary.

It is important to point out that all conventional, longitudinally one-dimensional radionuclide transport models for rivers and estuaries [e.g., U.S. Nuclear Regulatory Commission (1977), White and Eckerman (1982)] include implicitly the effect of the convection-defect radionuclide transport rate in their general empirical formulations of the "longitudinal dispersion radionuclide transport rate" based on the product of (1) the questionable "longitudinal radionuclide dispersion coefficient," which is generally specified differently for each different river or estuary, and (2) the longitudinal gradient of cross-section-averaged water concentration of the radionuclide in the water layer of the main flow channel, in order to develop "dispersion transport" type submodels that are conceptually similar to the conventional turbulent eddy-diffusion type submodels.

However, in contrast to the conventional, longitudinally one-dimensional radionuclide transport models [e.g., U.S. Nuclear Regulatory Commission (1977), White and Eckerman (1982)], the present development of the nonconvective radionuclide transport submodel rigorously formulates the explicit form of the convection-defect radionuclide transport rate in the water layer $\overline{G}^{**}_{rw,x}$ [Eqs. (3.50), (3.51a), and (3.51b)] in terms of (1) longitudinally local channel flow rate $\overline{G}_x$ and (2) longitudinally local effective value of maximum vertical water concentration difference in the water layer $\overline{\Delta C}^{*}_{rw,\max}$ [Eqs. (3.34) and (3.36)], which depends on the longitudinally local water concentration of the radionuclide in the water layer and the detailed geometric characteristics of the cross section of the main flow channel. Particularly, it is important to point out that the present explicit form of the convection-defect radionuclide transport rate $\overline{G}^{**}_{rw,x}$ [Eqs. (3.50), (3.51a), and (3.51b)] correctly excludes the effect of the longitudinal gradient of the water concentration of the radionuclide in the water layer $\partial\overline{C}_{rw}/\partial x$ in the formulation of the fast-transient, longitudinally one-dimensional, nonconvective radionuclide transport rate. In contrast, the conventional formulations [e.g., U.S. Nuclear Regulatory Commission (1977), White and Eckerman (1982)] incorrectly include the convection-defect radionuclide transport rate as an integral part of the longitudinal dispersion radionuclide transport rate in terms of the product of the longitudinal radionuclide dispersion coefficient and the longitudinal gradient of the water concentration of the radionuclide in the water layer $\partial\overline{C}_{rw}/\partial x$ in the main flow channel.

The particular explicit formulation of the convection-defect radionuclide transport rate $\overline{G}^{**}_{rw,x}$ [Eqs. (3.50), (3.51a), and (3.51b)] is an important novel feature of the present fast-transient, one-dimensional, two-layer, discrete-element radionuclide transport model and its associated RADONE computer code for controlled rivers and tidal estuaries.

The integrand, consisting of the $(\overline{V'_x C'_{rw}})$ part of the integral form of the eddy-turbulent radionuclide transport rate [Eq. (3.46)] represents the eddy-turbulent radionuclide transport flux (along the curvilinear longitudinal x-axis of the main flow channel). According to conventional development of first order closure approximation associated with turbulent flow analysis, eddy-turbulent radionuclide transport flux $(\overline{V'_x C'_{rw}})$ can be formulated as the product of (1) the local coefficient of eddy-turbulent radionuclide transport $\epsilon_{rw,xx}$, where the subscript xx represents the cross-sectional area being normal and the direction of the transport being along the curvilinear longitudinal x-axis of the main flow channel, respectively, and (2) the longitudinal gradient (along the curvilinear longitudinal x-axis of the main flow channel) of the temporally primary-scale water concentration of the radionuclide in the water layer $C_{rw}(t,x,y,z)$ [Eqs. (3.28), (3.35a), and (3.35b)]; that is

$$\overline{(V_x'C_{rw}')} = -\,\epsilon_{rw,xx}\left[\frac{\partial C_{rw}}{\partial x}(t,x,y,z)\right] = -\,\epsilon_{rw,xx}\left[\frac{\partial \overline{C}_{rw}}{\partial x}(t,x) + \frac{\partial \overline{C}^{*}_{rw}}{\partial x}(t,x,y,z)\right] \; . \tag{3.52a}$$

Considering the simplified expression, which does not explicitly indicate the variation with time and the x-coordinate along the main flow channel, but which only indicates explicitly the vertical and lateral variations over the cross section of the main flow channel, the eddy-turbulent radionuclide transport flux can be represented in an equivalent form as

$$\overline{(V_x'C_{rw}')} = -\,\epsilon_{rw,xx}\left[\frac{\partial \overline{C}_{rw}}{\partial x} + \frac{\partial \overline{C}^{*}_{rw}}{\partial x}(y,\eta)\right] \; . \tag{3.52b}$$

Eddy-turbulent radionuclide transport flux $\overline{(V_x'C_{rw}')}$ [Eqs. (3.52a) and (3.52b)] consists only of the phenomenological effect of eddy-turbulent fluctuations and specifically excludes the effect of the longitudinal dispersion phenomenon, which is considered separately in the formulation of the convection-defect radionuclide transport rate $\overline{G}^{**}_{rw,x}$ [Eqs. (3.50), (3.51a), and (3.51b)]. Hence, according to the fundamental considerations of the eddy-turbulent fluctuations, the Reynolds hypothesis [e.g., Schlichting (1960), Goldstein (1938)] can be used to establish the phenomenological equivalence between eddy-turbulent momentum transport and eddy-turbulent radionuclide transport by assuming completely isotropic eddy-turbulent fluctuations in the main flow channel with a single isotropic coefficient of eddy-turbulent transport $\epsilon(y,\eta)$ as

$$\epsilon_{rw,xx} \simeq \epsilon(y,\eta) \; . \tag{3.53}$$

Considering the generalized form of the self-similar, combined vertical and lateral variation, over the cross section of the main flow channel of the magnitude of the local eddy-turbulent shear stress that is consistent with the assumed Blasius power-law-type, self-similar, combined vertical and lateral variation of the channel flow velocity V_x [Eqs. (3.31a) and (3.31b)], the self-similar, combined vertical and lateral variation, over the cross section of the main flow channel, of the isotropic coefficient of eddy-turbulent transport $\epsilon(y,\eta)$ can be formulated [Eraslan (1983)] as

$$\epsilon(y,\eta) = \left\{ n\left[\frac{(n+1)}{n}\right]^{\frac{(n-l)}{(n+1)}} \beta^{\frac{2n}{(n+1)}} \right\} \left[\frac{1}{\langle D^2\rangle^{\frac{(n-l)}{(n+1)}}}\right] \left[\overline{\mathrm{Re}}^{\frac{(n-l)}{(n+1)}}\right] \nu$$

$$\times \left\{ [D(y)]^{\frac{2(n-l)}{(n+1)}} \right\} \left[\eta(1-\eta)^{\frac{(n-l)}{n}} \right] \; . \tag{3.54}$$

Therefore, considering the self-similar, combined vertical and lateral variation of the isotropic coefficient of eddy-turbulent transport $\epsilon(y,\eta)$ [Eq. (3.54)] to be equivalent to the local coefficient of eddy-turbulent radionuclide transport $\epsilon_{rw,xx}$ [Eq. (3.53)] and the form of the longitudinal gradient (along the curvilinear longitudinal x-axis of the main flow channel) of the temporally primary-scale water concentration of the radionuclide in the water layer, associated with the eddy-turbulent radionuclide transport flux [Eqs. (3.52a) and (3.52b)], the integral form of the eddy-turbulent radionuclide transport rate $\overline{G}''_{rw,x}$ [Eq. (3.46)] can be formulated as

$$\overline{G}''_{rw,x} = \int_{B_{wf}} \int_0^1 \left\{ -\,\epsilon(y,\eta) \left[\frac{\partial \overline{C}_{rw}}{\partial x} + \frac{\partial \overline{C}^*_{rw}}{\partial x}(y,\eta) \right] \right\} D(y)\, d\eta\, dy$$

$$= -\left[\int_{\overline{B}_{wf}} \int_0^1 \epsilon(y,\eta) D(y)\, d\eta\, dy \right] \frac{\partial \overline{C}_{rw}}{\partial x} - \int_{\overline{B}_{wf}} \int_0^1 \epsilon(y,\eta) \frac{\partial \overline{C}^*_{rw}}{\partial x}(y,\eta) D(y)\, d\eta\, dy \ . \tag{3.55}$$

Considering the assumed self-similar form of the water concentration of the radionuclide in the water layer, with variations along the vertical and lateral directions over the cross section of the main flow channel [Eqs. (3.35a) and (3.35b)], the computational form of the eddy-turbulent radionuclide transport rate [Eq. (3.55)] can be formulated as

$$\overline{G}''_{rw,x} = \overline{A}\left(-\,\overline{E}''_{rw} \frac{\partial \overline{C}_{rw}}{\partial x} \right) + \overline{A}\left[-\,\overline{E}''_{rw} \frac{\partial}{\partial x}\left(\frac{\langle D^2 \rangle}{2\overline{D}\overline{D}_{\max}} \overline{\Delta C}^*_{rw,\max} \right) + \overline{E}''^{*}_{rw,2} \frac{\partial}{\partial x}\left(\frac{\overline{\Delta C}^*_{rw,\max}}{\overline{D}_{\max}} \right) \right] \ . \tag{3.56}$$

The local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport, associated with the longitudinal gradient (along the curvilinear longitudinal x-axis of the main flow channel) of the water concentration of the radionuclide in the water layer C'_{rw} is defined as

$$\overline{E}''_{rw} = \int_{\overline{B}_{wf}} \int_0^1 \epsilon(y,\eta) D(y)\, d\eta\, dy \ , \tag{3.57}$$

which can be readily evaluated in integrated form by using the self-similar, combined vertical and lateral variation, over the cross section of the main flow channel, of the isotropic coefficient of eddy-turbulent transport $\epsilon(y,\eta)$ [Eq. (3.54)], as

$$\overline{E}''_{rw} = \overline{C}''_{n,\beta} \overline{C}''_{n,D} \left[\mathrm{Re}^{\frac{(n-1)}{(n+1)}} \nu \right] \ , \tag{3.58}$$

where

$$\overline{C}''_{n,\beta} = \frac{n^3}{(2n-1)(3n-1)} \left[\frac{(n+1)}{n} \right]^{\frac{(n-1)}{(n+1)}} \beta^{\frac{2n}{(n+1)}} \ , \tag{3.59}$$

and

$$\overline{C}''_{n,D} = \frac{\langle D^{\frac{(3n-l)}{(n+1)}} \rangle}{\overline{D}\langle D^2 \rangle^{\frac{(n-l)}{(n+1)}}} \quad . \tag{3.60}$$

Similarly, the local, cross-section-averaged secondary coefficient of eddy-turbulent radionuclide transport, associated with the longitudinal gradient (along the curvilinear longitudinal x-axis of the main flow channel) of the effective value of local maximum vertical water concentration difference of the radionuclide in the water layer $\overline{\Delta C^{*}_{rw,\max}}$ is defined as

$$\overline{E}''^{*}_{rw,2} = \int_{B_{wf}} \int_{0}^{1} \epsilon(y,\eta) D^2(y)(3\eta^2 - 2\eta^3) d\eta dy \quad , \tag{3.61}$$

which can be readily evaluated in integrated form by using the self-similar, combined vertical and lateral variation, over the cross section of the main flow channel, of the isotropic coefficient of eddy-turbulent transport $\epsilon(y,\eta)$ [Eq. (3.54)] as

$$\overline{E}''^{*}_{rw,2} = \overline{C}'^{*}_{2,n,\beta} \overline{C}'^{*}_{2,n,D} \left[\mathrm{Re}^{\frac{(n-l)}{(n+1)}} \nu \right] \quad , \tag{3.62}$$

where

$$\overline{C}'^{*}_{2,n,\beta} = \frac{6n^5(10n-3)}{(2n-1)(3n-1)(4n-1)(5n-1)(6n-1)} \left[\frac{(n+1)}{n} \right]^{\frac{(n-l)}{(n+1)}} \beta^{\frac{2n}{(n+1)}} \quad , \tag{3.63}$$

and

$$\overline{C}'^{*}_{2,n,D} = \frac{\langle D^{\frac{4n}{(n+1)}} \rangle}{\overline{D}^2 \langle D^2 \rangle^{\frac{(n-l)}{(n+1)}}} \quad . \tag{3.64}$$

The three product terms that constitute the local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport $\overline{E}''_{rw}$ [Eq. (3.55)] represent:

1. The first product term, dimensionless coefficient $\overline{C}''_{n,\beta}$ [Eq. (3.58)], represents explicitly the overall effect of the assumed self-similar variation of the isotropic coefficient of eddy-turbulent transport $\epsilon(y,\eta)$ [Eq. (3.54)], which is consistent with the assumed Blasius power-law-type, self-similar vertical variation of channel flow velocity over a uniform, rectangular, cross-sectional area. The effect of varying depth conditions along the lateral direction of the cross section of the main flow channel is not included. The explicit form of the first dimensionless coefficient term $\overline{C}''_{n,\beta}$ [Eq. (3.59)] includes (a) the power n of the Blasius power-law-type, self-similar vertical variation (with a suggested value of $n = 8$) and (b) the constant bottom friction coefficient (with a suggested universally constant value of $\beta = 0.2$).

2. The second product term, dimensionless coefficient $\overline{\mathcal{C}}''_{n,D}$ [Eq. (3.60)], represents explicitly the geometric factor associated with the overall effect of the detailed geometric characteristics of the actual nonuniform and nonrectangular cross-sectional area, with depth conditions varying along the lateral direction of the cross section of the main flow channel. The explicit form of the dimensionless geometric factor includes (a) average depth $\overline{D}$ of the cross section of the main flow channel, (b) the second mean-integral moment of depth $\langle D^2 \rangle$ [Eq. (3.32)] of the cross section of the main flow channel, and (c) the $(3n - 1)/(n + 1)$ mean-integral moment of depth, representing the moment of the $(3n - 1)/(n + 1)$ power of the depth variation over the lateral surface width of the cross section as

$$\langle D^{\frac{(3n-1)}{(n+1)}} \rangle = \frac{1}{\overline{B}_{srf}} \int_{\overline{B}_{srf}} [D(y)]^{\frac{(3n-1)}{(n+1)}} \, dy \quad . \tag{3.65}$$

   Values of average depth and the mean-integral moments of depth are evaluated according to the variation of depth along the lateral direction of the cross section, based on the specified profile of the bed contour of the cross section of the main flow channel.

3. The third product term represents the effective coefficient of isotropic eddy-turbulent transport, which is formulated according to conventional scaling of the constant coefficient of kinematic viscosity of water ν with the cross-sectional Reynolds number $\overline{\mathrm{Re}}$ [Eq. (3.39)] based on the temporally primary-scale and spatially primary-scale principal transportive intrinsic flow variables of the longitudinally one-dimensional transport model. Consistent with the standard formulations of turbulent flow conditions, the effective coefficient of isotropic eddy-turbulent transport includes the $(n - 1)/(n + 1)$ power of the cross-sectional Reynolds number $\overline{\mathrm{Re}}$ [Eq. (3.39)], which represents the effect of the increasing value of effective eddy-turbulent mixing conditions with increasing velocity conditions in a rectangular cross-sectional channel.

Similarly, the three product terms that constitute the local, cross-section-averaged secondary coefficient of eddy-turbulent radionuclide transport $\overline{E}'^{*}_{rw,2}$ [Eq. (3.59)] represent:

1. The first product term, the dimensionless coefficient $\overline{\mathcal{C}}'^{*}_{2,n,\beta}$ [Eq. (3.63)], represents explicitly the overall effect of (a) the assumed self-similar vertical variation of the isotropic coefficient of eddy-turbulent transport $\epsilon(y,\eta)$ [Eq. (3.54)], which is consistent with the assumed Blasius power-law-type, self-similar, vertical variation of channel flow velocity over a uniform, rectangular, cross-sectional area, without including the effect of varying depth along the lateral direction of the cross section of the main flow channel, and (b) the assumed self-similar cubic form of the vertical variation of the longitudinal gradient of the temporally primary-scale water concentration of the radionuclide in the water layer $C_{rw}(t,x,y,z)$ [Eqs. (3.52a) and (3.52b)]. The explicit form of the first dimensionless coefficient $\overline{\mathcal{C}}'^{*}_{2,n,\beta}$ [Eq. (3.63)] includes (a) the power of the Blasius power-law-type, self-similar vertical distribution (with a suggested value of $n = 8$) and (b) the constant bottom friction coefficient (with a suggested universally constant value of $\beta = 0.2$).
2. The second product product term, the dimensionless coefficient $\overline{\mathcal{C}}'^{*}_{2,n,D}$ [Eq. (3.64)], represents explicitly the geometric factor associated with the overall effect of the detailed geometric characteristics of the nonuniform and nonrectangular cross-sectional area, with depth conditions varying along the lateral direction of the cross section of the main flow channel. The explicit form of the dimensionless geometric factor includes (a) average depth $\overline{D}$ of the cross section of the main flow

channel, (b) the second mean-integral moment of depth $\langle D^2 \rangle$ [Eq. (3.32)] of the cross section of the main flow channel, and (c) the $4n/(n + 1)$ mean-integral moment of depth, representing the moment of the $4n/(n + 1)$ power of depth variation over the lateral surface width of the cross section of the main flow channel as

$$\langle D^{\overline{\frac{4n}{(n+1)}}} \rangle = \frac{1}{\overline{B}_{srf}} \int_{\overline{B}_{srf}} [D(y)]^{\overline{\frac{4n}{(n+1)}}} dy \quad . \tag{3.66}$$

Values of average depth and the mean-integral moments of depth are evaluated according to the variation of depth along the lateral direction of the cross section, based on the specified profile of the bed contour of the cross section of the main flow channel.

3. The third product term again represents the effective coefficient of isotropic eddy-turbulent transport, which is formulated according to the conventional scaling of the constant coefficient of kinematic viscosity of water ν with the cross-sectional Reynolds number $\overline{Re}$ [Eq. (3.39)] based on the temporally primary-scale and spatially primary-scale, principal transportive intrinsic flow variables of the longitudinally one-dimensional transport model. Consistent with standard formulations of turbulent flow conditions, the effective coefficient of isotropic eddy-turbulent transport includes the $(n - 1)/(n + 1)$ power of the cross-sectional Reynolds number $\overline{Re}$ [Eq. (3.39)], which represents the effect of the increasing value of the effective eddy-turbulent mixing conditions under increasing velocity conditions in a rectangular cross-sectional channel.

The present formulation of eddy-turbulent radionuclide transport rate $\overline{G}''_{rw,x}$ [Eqs (3.55) through (3.66)] represents explicitly the part of the longitudinal radionuclide transport rate associated only with eddy-turbulent mixing conditions in the main flow channel. The formulation is based on the standard development of conventional turbulent flow analysis [e.g., Goldstein (1938), Schlichting (1948)], which considers only mixing conditions that result from temporal and spatial averaging [Eq. (3.55)] of temporally subscale and spatially subscale eddy-turbulent fluctuations of the channel flow velocity V_x [Eq. (3.27)] and the water concentration of the radionuclide in the water layer C_{rw} [Eq. (3.28)] over the cross section of the main flow channel.

The eddy-turbulent radionuclide transport rate $\overline{G}''_{rw,x}$ [Eqs. (3.55) through (3.66)] specifically excludes the direct contribution of any convection-defect-type radionuclide transport effect associated with the "radionuclide dispersion" phenomenon, which also contributes to the overall nonconvective longitudinal radionuclide transport (along the curvilinear longitudinal x-axis of the main flow channel). Hence, the present development of the eddy-turbulent radionuclide transport rate $\overline{G}''_{rw,x}$ [Eqs. (3.55) through (3.66)] uses correctly and appropriately two well-established assumptions of turbulent flow analysis as (1) the Reynolds hypothesis [e.g., Goldstein (1938), Schlichting (1960)], which represents the phenomenological equivalence between eddy-turbulent momentum transport and eddy-turbulent transport of any other transportive intrinsic flow variable, including the water concentration of the radionuclide in the water layer, and (2) the assumption of locally isotropic turbulence conditions [e.g., Goldstein (1938), Schlichting (1960)] because the formulation considers strictly the eddy-turbulent mixing conditions in the main flow channel.

The present formulation of the eddy-turbulent radionuclide transport rate $\overline{G}''_{rw,x}$ [Eqs. (3.55) through (3.66)] is based on two effective coefficients of longitudinal radionuclide transport as (1) the local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport $\overline{E}''_{rw}$ [Eqs. (3.57) through (3.60)] and (2) the local cross-section-averaged secondary coefficient of eddy-turbulent radionuclide transport $\overline{E}'^{*}_{rw,2}$ [Eqs. (3.61) through (3.64)]. The explicit formulations of these two effective coefficients of eddy-turbulent radionuclide transport are strictly based on standard turbulent flow analysis [e.g., Goldstein (1938), Schlichting (1960)] and the assumed temporally primary-scale, self-similar, combined vertical and lateral variations of the principal, transportive intrinsic flow variables: channel flow velocity $V_x(y,\eta)$ [Eqs. (3.31a) and (3.31b)] and water concentration of the radionuclide in the water layer $C_{rw}(y,\eta)$ [Eqs. (3.35a) and (3.35b)]. Therefore, they do not require any additional information about longitudinal mixing conditions in the main flow channel of a river or an estuary. It is important to note that all conventional longitudinally one-dimensional radionuclide transport models [e.g., U.S. Nuclear Regulatory Commission (1977), White and Eckerman (1982)] require additional information about longitudinal mixing conditions in a river or an estuary, in the form of longitudinal radionuclide dispersion coefficients that generally must be specified differently for each different river or estuary. Since the formulations of the overall longitudinal radionuclide transport rates in these conventional longitudinally one-dimensional radionuclide transport models [e.g., U.S. Nuclear Regulatory Commission (1977), White and Eckerman (1982)] include implicitly the combined effects of both convection-defect radionuclide transport and eddy-turbulent radionuclide transport, it becomes impossible to determine the required forms of the longitudinal radionuclide dispersion coefficients with acceptable levels of universal applicability similar to the levels of universal applicability of the standard conventional turbulent flow analysis.

The present development of the longitudinal nonconvective radionuclide transport submodel eliminates this problem, which is common to all conventional, longitudinally one-dimensional, radionuclide transport models [e.g., U.S. Nuclear Regulatory Commission (1977), White and Eckerman (1982)], by considering separately the eddy-turbulent radionuclide transport rate $\overline{G}''_{rw,x}$ [Eqs. (3.55) through (3.66)] in terms of two effective coefficients of longitudinal radionuclide transport as (1) the local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport $\overline{E}''_{rw}$ [Eqs. (3.57) through (3.60)] and (2) the local, cross-section-averaged secondary coefficient of eddy-turbulent radionuclide transport $\overline{E}''^{*}_{rw,s}$ [Eqs. (3.61) through (3.64)]. Both coefficients are formulated explicitly based on (a) standard, conventional turbulent flow analysis [e.g., Goldstein (1938), Schlichting (1960)], (b) assumed temporally primary-scale, self-similar combined vertical and lateral variations of the principal, transportive intrinsic flow variables: channel flow velocity $V_x(y,\eta)$ [Eqs. (3.31a) and (3.31b)] and water concentration of the radionuclide in the water layer $C_{rw}(y,\eta)$ [Eqs. (3.35a) and (3.35b)], and (c) the detailed geometric characteristics of the cross section of the main flow channel of the river or the estuary.

The explicit formulation of the eddy-turbulent radionuclide transport rate $\overline{G}''_{rw,x}$ [Eqs. (3.55) through (3.66)] is another important, novel feature of the fast-transient, one-dimensional, two-layer radionuclide transport model of the RADONE computer code that is both conceptually and computationally different from the formulations of all other longitudinally one-dimensional radionuclide transport models [e.g., U.S. Nuclear Regulatory Commission (1977), White and Eckerman (1982)] for controlled rivers and tidal estuaries.

The nonconvective radionuclide transport rate $\overline{G}_{rw,x}$ [Eq. (3.43)] can be formulated by combining (1) the computational form of the molecular radionuclide transport rate $\overline{G}_{rw,mol,x}$ [Eq. (3.49)], (2) the computational form of the convection-defect radionuclide transport rate $\overline{G}^{**}_{rw,x}$ [Eqs. (3.50), (3.51a), and (3.51b)], and (3) the computational form of the eddy-turbulent radionuclide transport rate $\overline{G}''_{rw,x}$ [Eqs. (3.56) through (3.66)] as

$$\overline{G}_{rw,x} = \overline{A}\left(-\,\epsilon_{rw,\min}\frac{\partial\overline{C}_{rw}}{\partial x}\right) + \left(C^{*}_{n,D}\overline{\Delta C^{*}_{rw,\max}}\right)\overline{G}_x + \overline{A}\left(-\,\overline{E}''_{rw}\frac{\partial\overline{C}_{rw}}{\partial x}\right)$$

$$+\,\overline{A}\left[-\,\overline{E}''_{rw}\,\frac{\partial}{\partial x}\left(\frac{\langle D^2\rangle}{2\overline{D}\overline{D}_{\max}}\,\overline{\Delta C}^{*}_{rw,\max}\right)+\overline{E}''^{*}_{rw,2}\,\frac{\partial}{\partial x}\left(\frac{\overline{\Delta C}^{*}_{rw,\max}}{\overline{D}_{\max}}\right)\right]\;, \tag{3.67}$$

which can be rearranged, by combining the first term and the third term on the right side of Eq. (3.67), to obtain the final computational form of the nonconvective radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel $\overline{G}''_{rw,x}$ [Eqs. (3.43) and (3.47)] as

$$\overline{G}_{rw,x}=\left(C^{*}_{n,D}\,\overline{\Delta C}^{*}_{rw,\max}\right)\overline{G}_x+\overline{A}\left[-\,(\epsilon_{rw,\min}+\overline{E}''_{rw})\,\frac{\partial\overline{C}_{rw}}{\partial x}\right]$$

$$+\,\overline{A}\left[-\,\overline{E}''_{rw}\,\frac{\partial}{\partial x}\left(\frac{\langle D^2\rangle}{2\overline{D}\overline{D}_{\max}}\,\overline{\Delta C}^{*}_{rw,\max}\right)+\overline{E}''^{*}_{rw,2}\,\frac{\partial}{\partial x}\left(\frac{\overline{\Delta C}^{*}_{rw,\max}}{\overline{D}_{\max}}\right)\right]\;. \tag{3.68}$$

All terms on both sides of the final computational form of the nonconvective radionuclide transport rate $\overline{G}''_{rw,x}$ [Eq. (3.68)] are evaluated at the same two auxiliary locations $i - ½$ and $i + ½$, corresponding to the locations of the upstream and downstream enclosure surfaces of the element i of the channel segment. All the derivative terms along the curvilinear longitudinal x-axis of the main flow channel are formulated, based on standard half-point forms for the general flow quantity $\overline{f}$, as:

$$\left(\frac{\partial\overline{f}}{\partial x}\right)_{i-½}=\frac{2}{(\Delta x_i+\Delta x_{i-1})}\,(\overline{f}_i-\overline{f}_{i-1})\;, \tag{3.69a}$$

$$\left(\frac{\partial\overline{f}}{\partial x}\right)_{i+½}=\frac{2}{(\Delta x_i+\Delta x_{i+1})}\,(\overline{f}_{i+1}-\overline{f}_i)\;, \tag{3.69b}$$

where the general flow quantity $\overline{f}$ represents the differentiated parts of the three derivative terms as

$$\overline{f}=\overline{C}_{rw}\;, \tag{3.70a}$$

$$\overline{f}=\left(\frac{\langle D^2\rangle}{2\overline{D}\overline{D}_{\max}}\,\overline{\Delta C}^{*}_{rw,\max}\right)\;, \tag{3.70b}$$

$$\overline{f}=\left(\frac{\overline{\Delta C}^{*}_{rw,\max}}{\overline{D}_{\max}}\right)\;. \tag{3.70c}$$

The final computational form of the nonconvective radionuclide transport rate $\overline{G}''_{rw,x}$ [Eq. (3.68)] eliminates the auxiliary terms of the discrete-element equation for water concentration of the radionuclide in the water layer [Eqs. (2.4) and (2.6)] in terms of (1) principal solution variables, consisting of the channel flow rate $\overline{G}_x$ and water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ and (2) standard geometric variables of the cross section of the main flow channel. For brevity and convenience the subscripts $i - ½$ and $i + ½$ of the auxiliary terms representing the nonconvective radionuclide transport rates at the upstream enclosure surface at $i - ½$ and at the downstream enclosure surface at $i + ½$, respectively, of element i [Eqs. (2.4) and (2.6)] are not included in the general computational form of the nonconvective radionuclide transport rate $\overline{G}''_{rw,x}$ [Eq. (3.68)].

3.5 FORMULATION OF BOTTOM RADIONUCLIDE TRANSPORT SUBMODEL

The modeling of the complete radionuclide transport phenomenon between the water layer and the bottom layer of the main flow channel of a river or an estuary requires careful consideration of various individual transport phenomena associated with (1) bottom-mixing conditions, (2) settling (deposition) and resuspension (scouring) conditions of different sediment classes and different organic matter, and (3) adsorption-desorption characteristics of the radionuclide on different sediment classes and sorption (adsorption and/or absorption)-desorption characteristics of the radionuclide on/in different organic matter. Accurate and detailed consideration of each of these phenomena that can control the overall radionuclide transport conditions between the water layer and the bottom layer of the main flow channel generally becomes an extremely difficult, although not insurmountable, task from mathematical modeling considerations. More importantly, even though an extremely detailed and accurate mathematical submodel can be developed, which can consider all the detailed and complex physical phenomena that control the transport of the radionuclide between the water layer and the bottom layer, it may still be impossible to utilize such a submodel in site-specific applications, because the essential field-measured information and the experimental data, which can only be obtained by controlled laboratory experiments, usually will not be readily available for specifying all the parameters and coefficients that will be involved in the modeling of each individual transport phenomenon in the main flow channel of a river or an estuary (Sect. 1.3).

Considering the fundamental rationale in the development of the fast-transient, one-dimensional, two-layer radionuclide transport model of the RADONE computer code (Sect. 1.3), it is important to point out that the development of the necessary bottom radionuclide transport submodel is not intended for detailed and accurate modeling of all the physical mechanisms that constitute each individual complex phenomenon; but, more appropriately, it is intended for establishing a physically realistic and mathematically plausible submodel which can approximately incorporate the overall effect of each individual physical phenomenon that controls the vertical transport of the radionuclide between the water layer and the bottom layer of the main flow channel of a river or an estuary. Therefore, the subsequent development of the bottom radionuclide transport submodel will be based on physically realistic, approximate, and relatively simple formulations of the three important transport phenomena associated with (1) bottom-mixing conditions, (2) bottom-settling (deposition) conditions, and (3) bottom-resuspension (scouring) conditions, which control the overall vertical radionuclide transport between the water layer and a bottom layer of the main flow channel of a river or an estuary.

The net bottom radionuclide transport rate $\overline{G}_{rw,bot}$ [Eqs. (2.4) and (2.8)] between the water layer and the bottom layer is formulated approximately in terms of three parts, representing the individual contributions of the vertical radionuclide transport fluxes associated with the three individual physical phenomena that control the vertical transport of the radionuclide, between the water layer and the bottom layer, in the main flow channel, as

$$\overline{G}_{rw,bot} = \Delta x\, \Gamma(\overline{g}_{rw,turb} + \overline{g}_{rw,fall} + \overline{g}_{rw,susp}) \ , \tag{3.71}$$

where

$\bar{g}_{rw,turb}$ = bottom-mixing radionuclide transport flux, between the water layer and the bottom layer, associated with the cumulative vertical transport effect of molecular diffusion and eddy-turbulent diffusion in the water layer, which results in the vertical transport of the radionuclide in the main flow channel (influx into the water layer from the bottom layer assumed as positive),

$\bar{g}_{rw,fall}$ = bottom-settling (deposition) radionuclide transport flux, from the water layer into the bottom layer, associated with the cumulative vertical transport effect of settling (deposition), from the water layer, into the bottom layer of (1) different classes of sediment that contain the radionuclide in the adsorbed state on multiple classes of sediment and (2) different organic matter that contain the radionuclide in the sorbed (adsorbed and/or absorbed) state on/in different organic matter, in the main flow channel (outflux from the water layer into the bottom layer assumed as negative), and

$\bar{g}_{rw,susp}$ = bottom-resuspension (scouring) radionuclide transport flux, from the bottom layer into the water layer, associated with the cumulative vertical transport effect of resuspension (scouring), from the bottom layer, into the water layer of (1) different classes of sediment that contain the radionuclide in the adsorbed state on multiple classes of sediment and (2) different organic matter that contain the radionuclide in the sorbed (adsorbed and/or absorbed) state on/in different organic matter, in the main flow channel (in flux into the water layer from the bottom layer assumed as positive).

The formulation of each individual bottom radionuclide transport flux term is based on approximate, but physically realistic and mathematically plausible, consideration of each particular physical phenomenon that can control the particular mode of vertical transport of the radionuclide between the water layer and the bottom layer in the main flow channel.

3.5.1 Formulation of Bottom-Mixing Radionuclide Transport Flux

The formulation of the bottom-mixing radionuclide transport flux, between the water layer and the bottom layer, is based on approximate consideration of the cumulative mixing phenomenon, consisting of the molecular diffusion phenomenon and turbulent diffusion phenomenon, which contribute to the vertical transport of the radionuclide in the water layer of the main flow channel.

It is important to point out that the net effect of the eddy-turbulent diffusion phenomenon, which results in vertical transport of the radionuclide between the water layer and the bottom layer, should not be based on the value an eddy-turbulent diffusion coefficient evaluated at the bottom of the main flow channel. Since the water layer represents the vertical column of water which contains the radionuclide in different states, including the dissolved state in the water mixture, the adsorbed state on multiple sediment classes, and the sorbed (adsorbed and/or absorbed) state in and/or on different organic matter, the vertical mixing phenomena that transport the radionuclide between the water layer and the bottom layer should not be represented by the local mixing effects that occur at the bottom plane of the water layer; they should be represented, based on physical considerations, by the overall mixing effect that occurs, in the general sense, over the depth of the water column, which represents the water layer in the main flow channel. Therefore, it is more realistic, based on considerations of the physical conditions, to incorporate an effective, cross-section-averaged value for the eddy-turbulent mixing effects in representing the cumulative vertical eddy-turbulent mixing phenomena that occur in the water layer of the main flow channel.

Hence, the formulation of the bottom-mixing radionuclide transport flux $\bar{g}_{rw,turb}$, between the water layer and the bottom layer, is based on the scaled value of the local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport $\bar{E}''_{rw}$ [Eqs. (3.57) through (3.60], in the water layer as

$$\bar{g}_{rw,turb} = - R_{bot,turb}(\epsilon_{bot,\min} + k_{rw,bot}\bar{E}''_{rw})\left[\frac{1}{\bar{D}}\left(\bar{C}_{rw} - \bar{C}_{rb}\right)\right] . \tag{3.72}$$

The parameter $R_{bot,turb}$ is included as a specified constant coefficient of effective depth of vertical mixing, for representing the inverse of the part (as percent) of the local, average depth of the water layer where the effective part of the eddy-turbulent mixture in the main flow channel controls the vertical transport of the radionuclide between the water layer and the bottom layer. The parameter $k_{rw,bot}$ is included as a specified constant coefficient of effective vertical eddy-turbulent mixing, representing the scaling factor required for obtaining the value of the effective vertical eddy-turbulent mixing coefficient based on the value of the local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport $\bar{E}''_{rw}$ [Eqs. (3.57) through (3.60)]. The parameter $\epsilon_{bot,\min}$ is included as a specified constant minimum bottom diffusion coefficient (predominantly controlled by molecular diffusion effects) for bottom radionuclide transport between the water layer and the bottom layer under effectively zero flow conditions when vertical mixing occurs in the absence of main flow channel turbulence.

It is important to point out that it is not essential to determine extremely accurate values for the three parameters considered in the formulation of the bottom-mixing radionuclide transport flux $\bar{g}_{rw,turb}$ [Eq. (3.72)] for the simulation of the vertical bottom radionuclide transport conditions, between the water layer and the bottom layer, of the main flow channel. Indeed, the ranges of physically realistic values for the three parameters, consisting of (1) coefficient of effective depth of vertical mixing $R_{bot,turb}$, (2) coefficient of effective vertical eddy-turbulent mixing $k_{rw,bot}$, and (3) minimum bottom diffusion coefficient $\epsilon_{bot,\min}$, for evaluating the bottom-mixing radionuclide transport flux $\bar{g}_{rw,turb}$ [Eq. (3.72)], can be suggested as

$$1.0 \leqslant R_{bot,turb} \leqslant 4.0 \ , \tag{3.73a}$$

$$0.2 \leqslant k_{rw,bot} \leqslant 1.0 \ , \tag{3.73b}$$

$$\epsilon_{bot,\min} \simeq \epsilon_{rw,\min} \text{ [Eqs. (3.49) and (3.68)] } . \tag{3.73c}$$

Hence, based on realistic physical considerations, an approximate formulation of the bottom-mixing radionuclide transport flux $\bar{g}_{rw,turb}$ between the water layer and the bottom layer [Eq. (3.72)] can be obtained in terms of (1) the molecular diffusion [Eqs. (3.49), (3.68), and (3.73c)] and eddy-turbulent diffusion [Eqs. (3.57) through (3.60)] conditions in the water layer, (2) the specified constant parameter [Eqs. (3.73a) and (3.73b)], and (3) the radionuclide concentration difference between the local cross-section-averaged values of the water concentration of the radionuclide in the water layer $\bar{C}_{rw}$ and the bottom concentration of the radionuclide in the bottom layer in the main flow channel of a river or an estuary.

3.5.2 Formulation of Bottom-Settling Radionuclide Transport Flux

The formulation of the bottom-settling radionuclide transport flux, from the water layer into the bottom layer, is based on approximate consideration of the settling (deposition) phenomena, associated with (1) multiple sediment classes, which contain the radionuclide in the adsorbed states, and (2) different organic matter, which contain the radionuclide in the sorbed (adsorbed and/or absorbed) states, according to a sediment settling (deposition)-resuspension (scouring) submodel that was used successfully in various transient sediment transport models of the UTA project [e.g., Hetrick, Eraslan, and Patterson (1979)].

In the formulation of the bottom-settling radionuclide transport flux, it is assumed that all different classes of sediment, which contain the radionuclide in the adsorbed states, and all different organic matter, which contain the radionuclide in the sorbed (adsorbed and/or absorbed) states, can be combined into a lumped sediment-organic-matter class with a representative effective fall velocity in the water layer as

$\bar{V}_{rw\,fall}$ = effective fall velocity of the lumped sediment-organic-matter class, representing the average value of the fall velocities of all different classes of suspended sediment and all different suspended organic matter, which can contain the radionuclide in adsorbed states or in sorbed states, in the water layer.

It is important to note that, indeed, a realistic value for the effective fall velocity $\bar{V}_{rw\,fall}$ can be approximately estimated in the water layer of the main flow channel, provided that information can be obtained about the physicochemical composition of the water mixture, including the suspended states of multiple classes of sediment and different organic matter, in the main flow channel of a river or an estuary.

Hence, a physically realistic formulation of the bottom-settling (deposition) radionuclide transport flux $\bar{g}_{rw\,fall}$, from the water layer into the bottom layer, is based on a modified version of the sediment-settling (deposition)-resuspension (scouring) submodel [Hetrick, Eraslan, and Patterson (1979)] as

$$\bar{g}_{rw\,fall} = -\,R_{rw\,fall}\,\frac{\bar{V}_{rw\,fall}}{[1 + (|\bar{V}_x|/\bar{V}_{ref\,fall})^{p_{fall}}]}\,\bar{C}_{rw}\ . \tag{3.74}$$

The parameter $R_{rw\,fall}$ is included as a specified constant coefficient of effective fall speed, associated with the lumped sediment-organic-matter class in the water layer. The parameter $V_{rw,fall}$ is included as a specified constant reference value of channel flow speed of settling reduction, associated with the overall inhibiting effect of the local speed of flow on the settling (deposition) conditions of the lumped sediment-organic-matter class in the water layer. The parameter p_{fall} is included as a specified constant power of the ratio of the local speed $|\bar{V}_x|$ of the channel flow to the specified constant reference flow speed $\bar{V}_{ref\,fall}$ of settling reduction, associated with the overall inhibiting effect of the local speed of flow on the settling (deposition) rate of the lumped sediment-organic-matter class in the water layer.

Again, it is important to point out that it is not essential to determine extremely accurate values for the three parameters considered in the formulation of the bottom-settling radionuclide transport flux $\bar{g}_{rw\,fall}$ [Eq. (3.74)] for the simulation of the vertical bottom radionuclide transport conditions, between the water layer and the bottom layer, of the main flow channel. Indeed, the ranges of physically realistic values for the three parameters, consisting of (1) coefficient of effective fall speed $R_{w\,fall}$, (2) specified constant effective fall velocity of the lumped sediment-organic-matter class $\bar{V}_{rw\,fall}$, (3) specified constant reference flow speed of settling reduction $\bar{V}_{ref\,fall}$, and (4) specified constant power of the ratio of the local speed $|\bar{V}_x|$ of the channel flow to the specified constant reference flow speed $\bar{V}_{ref\,fall}$ of settling reduction, for evaluating the bottom-settling radionuclide transport flux $\bar{g}_{rw\,fall}$ [Eq. (3.74)], can be suggested as

$$0.5 \leqslant R_{rw\,fall} \leqslant 1.0 \ , \tag{3.75a}$$

$\overline{V}_{rw\,fall}$ = determined by averaging over the fall velocities of multiple classes of sediment and different organic matter, based on mass fractions in the water mixture , (3.75b)

$$2.0\ \mathrm{ft/s} \leqslant \overline{V}_{ref\,fall} = V_{ref} \leqslant 4.0\ \ \mathrm{ft/s} \ , \tag{3.75c}$$

$$0.5 \leqslant p_{fall} \simeq p_{rw} \leqslant 2.0 \ . \tag{3.75d}$$

Hence, based on realistic physical considerations, an approximate formulation of the bottom-settling radionuclide transport flux $\overline{g}_{rw\,fall}$, from the water layer into the bottom layer [Eq. (3.74)], can be obtained in terms of (1) the specified constant parameters $R_{w\,fall}$, $\overline{V}_{rw\,fall}$, $\overline{V}_{ref\,fall}$, and p_{fall} [Eqs. (3.75a) through (3.75d)] and (2) the local depth-averaged water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ in the main flow channel of a river or an estuary.

3.5.3 Formulation of Bottom-Resuspension Radionuclide Transport Flux

The formulation of the bottom-resuspension radionuclide transport flux, from the bottom layer into the water layer, is based on approximate considerations of the resuspension (scouring) phenomena, associated with (1) the multiple sediment classes, which contain the radionuclide in the adsorbed states, and (2) different organic matter, which contain the radionuclide in the sorbed (adsorbed and/or absorbed) states, again according to the sediment-settling (deposition)–resuspension (scouring) submodel, which was used successfully in various transient sediment transport models of the UTA project [e.g., Hetrick, Eraslan, and Patterson (1979)].

Again considering a lumped sediment-organic-matter class, which contains the radionuclide in all adsorbed and absorbed states, associated with all suspended and settled classes of sediment and different organic matter, a characteristics critical velocity $\overline{V}_{rb,susp}$, representing the overall resuspension (scouring) effects, from the bottom layer into the water layer, is defined in terms of the effective fall velocity $\overline{V}_{rw\,fall}$ [Eqs. (3.74) and (3.75c)], as

$\overline{V}_{rb,susp}$ = critical resuspension velocity of the lumped sediment-organic-matter class, representing the averaged threshold value of the critical resuspension velocities of all different classes of settled sediment and all different settled organic matter, which contain the radionuclide in adsorbed states or in absorbed states, in the bottom layer, such that

$$\overline{V}_{rb,susp} = 0.8\,\overline{V}_{rw\,fall} \ . \tag{3.76}$$

Considering that resuspension (scouring) effects generally depend on the bottom shear stress conditions, which are representative of the turbulent mixing conditions at the bottom of the main flow channel, a characteristic reference velocity value associated with the bottom shear stress is defined as

$\overline{V}_{fr,bot}$ = local bottom shear velocity, associated with the representation of the bottom shear stress conditions at the bottom of the water layer, between the water layer and the bottom layer.

The bottom shear velocity $\overline{V}_{fr,bot}$ can be formulated in terms of the bottom shear stress, which was previously used for the formulation of the bottom drag force per unit length (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (3.38a) and (3.38b)], consistent with the Blasius power-law-type of vertical distribution [e.g., Goldstein (1938)] and the assumed lateral distribution [Eqs. (3.31a) and (3.31b)], in its computational form, as

$$\overline{V}_{fr,bot} = \left\{ \left[\frac{(n+1)}{n} \right]^{\frac{n}{(n+1)}} \beta^{\frac{n}{(n+1)}} \nu \right\} \nu \left[\frac{\overline{A}^{\frac{n}{(n+1)}} \langle D^{\frac{(n-1)}{(n+1)}} \rangle}{B_{srf}^{\frac{n}{(n+1)}} \langle D^2 \rangle^{\frac{n}{(n+1)}} \overline{D}^{\frac{n}{(n+1)}}} \right] \tag{3.77a}$$

or, in a form which includes only the effect of depth variations, as

$$\overline{V}_{fr,bot} = \left\{ \left[\frac{(n+1)}{n} \right]^{\frac{n}{(n+1)}} \beta^{\frac{n}{(n+1)}} \mathrm{Re}^{\frac{n}{(n+1)}} \right\} \left[\frac{\langle D^{\frac{(n-1)}{(n+1)}} \rangle \overline{D}}{\langle D^2 \rangle^{\frac{n}{(n+1)}}} \right] \left(\frac{\nu}{D} \right) . \tag{3.77b}$$

The physical phenomena at the bottom of the main flow channel, which control the resuspension (scouring) of the settled (deposited) lumped sediment-organic-matter class, generally become activated at a threshold condition which can be directly related to the local bottom shear velocity $\overline{V}_{fr,bot}$ in the main flow channel. Therefore, the formulation of the bottom-resuspension radionuclide transport flux first considers the threshold conditions based on the comparison of the local bottom shear velocity $\overline{V}_{fr,bot}$ [Eqs. (3.77a) and (3.77b)] with the critical resuspension velocity $\overline{V}_{rb,susp}$ [Eq. (3.76)] to guarantee that no bottom-resuspension radionuclide transport flux can occur for local bottom shear stress conditions below the threshold conditions, that is,

$$\text{for } \overline{V}_{fr,bot} \leq \overline{V}_{rb,susp} \ : \ \overline{g}_{rw,susp} = 0 \ . \tag{3.78}$$

However, for local bottom shear stress conditions which exceed the threshold conditions, the formulation assumes that the resuspension rate of the settled (deposited) sediment-organic-matter class becomes proportional to the local bottom shear stress conditions, which can be related directly to the local bottom shear velocity $\overline{V}_{fr,bot}$ [Eqs. (3.79a) and (3.79b)]. Therefore, for the bottom local shear stress conditions, which exceed the threshold conditions, the bottom-resuspension radionuclide transport flux, from the bottom layer into the water layer, is formulated as

$$\text{for } \overline{V}_{fr,bot} > \overline{V}_{rb,susp} \ : \ \overline{g}_{rw,susp} = R_{rb,susp} \overline{V}_{fr,bot} \overline{C}_{rb} \ , \tag{3.79}$$

where the proportionality constant is defined as

$R_{rb,susp}$ = specified constant coefficient of resuspension, associated with the resuspension of the settled (deposited) sediment-organic-matter class from the bottom layer into the water layer, depending on the local bottom shear velocity conditions.

Again, it is important to note that it is not essential to determine extremely accurate values for the specified constant coefficient of resuspension $R_{rb,susp}$ in the formulation of the bottom-resuspension radionuclide transport flux $\overline{g}_{rw,susp}$ [Eq. (3.79)] for the simulation of the vertical bottom radionuclide transport conditions from the bottom layer into the water layer. The approximate values required for specifying the constant coefficient of resuspension $R_{rb,susp}$ can be readily obtained based on the values of

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coefficients used in the applications of the various sediment transport models for controlled rivers and tidal estuaries [e.g., Hetrick, Eraslan, and Patterson (1979)].

Hence, based on realistic physical considerations, an approximate formulation of the bottom resuspension radionuclide transport flux $\overline{g}_{rw,susp}$ [Eqs. (3.78) and (3.79)], from the bottom layer into the water layer, can be obtained in terms of (1) critical resuspension velocity $\overline{V}_{rb,susp}$ [Eq. (3.76)] or effective fall velocity $\overline{V}_{rf,fall}$, (2) local bottom shear velocity $\overline{V}_{fr,bot}$ [Eqs. (3.77a) and (3.77b)], (3) specified constant coefficient of resuspension $R_{rb,susp}$, and (4) local, bottom-depth-averaged bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$ in the main flow channel of a river or an estuary.

3.5.4 Formulation of Bottom Radionuclide Transport Rate for Water Layer and Bottom Layer

The net bottom radionuclide transport flux into the water layer $\overline{g}_{rw,bot}$, associated with the net bottom radionuclide transport rate, between the water layer and the bottom layer [Eq. (3.71)], can be formulated as the linear combination of its three individual parts, consisting of (1) bottom-mixing radionuclide transport flux $\overline{g}_{rw,turb}$ [Eq. (3.72)], (2) bottom-settling radionuclide transport flux $\overline{g}_{rw,fall}$ [Eq. (3.74)], and (3) bottom-resuspension radionuclide transport flux $\overline{g}_{rw,susp}$ [Eq. (3.79)], for the water layer in the main flow channel, as

$$\begin{aligned}\overline{g}_{rw,bot} &= \overline{g}_{rw,turb} + \overline{g}_{rw,fall} + \overline{g}_{rw,susp} \\ &= -R_{bot,turb}(\epsilon_{bot,\min} + k_{rw,bot}\overline{E}''_{rw})\left[\frac{1}{D}(\overline{C}_{rw} - \overline{C}_{rb})\right] \\ &\quad - R_{rw,fall}\frac{\overline{V}_{rw,fall}}{[1 + (|\overline{V}_x|/\overline{V}_{ref,fall})^{p_{fall}}]}\overline{C}_{rw} + \delta_{fr,susp}[R_{rb,susp}\overline{V}_{fr,bot}\overline{C}_{rb}] \ ,\end{aligned} \tag{3.80}$$

where

$\delta_{fr,susp}$ = integer control parameter (e.g., Kronecker delta) for representing the threshold conditions associated with the bottom-resuspension radionuclide transport flux [Eq. (3.78) or Eq. (3.79)],

= 0, for $\overline{V}_{fr,bot} \leq \overline{V}_{rb,susp}$,
= 1, for $\overline{V}_{fr,bot} > \overline{V}_{rb,susp}$.

The net bottom radionuclide transport flux into the bottom layer $\overline{g}_{rb,bot}$, across the enclosure surface between the water layer and the bottom layer, is evaluated directly as the negative of the net bottom radionuclide transport flux into the water layer $\overline{g}_{rw,bot}$ [Eq. (3.80)], in order to guarantee the conservation principle for the radionuclide as it is transported through the plane between the water layer and the bottom layer, i.e.,

$$\overline{g}_{rb,bot} = -\overline{g}_{rw,bot} \ . \tag{3.81}$$

Hence, the net bottom radionuclide transport rate into the water layer $\overline{G}_{rw,bot}$ [Eq. (3.71)], which is a part of the discrete-element equation for water concentration of the radionuclide in the water layer

[Eqs. (2.4) and (2.8)], can be formulated in terms of (1) the net bottom radionuclide transport flux into the water layer $\bar{g}_{rw,bot}$ [Eqs. (3.71) and (3.80)], (2) the length Δx (along the curvilinear longitudinal x-axis of the main flow channel) of the element, and (3) the length of the bed contour Γ of the element, as

$$\overline{G}_{rw,bot} = \Delta x \, \Gamma \, \bar{g}_{rw,bot} \; ; \tag{3.82}$$

and the corresponding net bottom radionuclide transport rate into the bottom layer $\overline{G}_{rb,bot}$ is formulated similarly, as

$$\overline{G}_{rb,bot} = \Delta x \, \Gamma \, \bar{g}_{rb,bot} \; , \tag{3.83a}$$

$$\overline{G}_{rb,bot} = \Delta x \, \Gamma (- \bar{g}_{rw,bot}) \; , \tag{3.83b}$$

$$G_{rb,bot} = - \overline{G}_{rw,bot} \; . \tag{3.83c}$$

The final computational form of the net bottom radionuclide transport rate into the water layer $\overline{G}_{rw,bot}$ [Eqs. (3.71), (3.72), (3.74), (3.79), and (3.82)] eliminates the auxiliary term of the discrete-element equation for water concentration of the radionuclide in the water layer [Eqs. (2.4) and (2.8)] in terms of (1) principal solution variables consisting of the channel flow rate $\overline{G}_x$, the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, and the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$ and (2) standard geometric variables of the cross section of the main flow channel. Similarly, the final computational form of the net bottom radionuclide transport rate into the bottom layer $\overline{G}_{rb,bot}$ [Eqs. (3.83a), (3.83b), and (3.83c)] eliminates the auxiliary term of the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eqs. (2.16) and (2.18)]. Again, for brevity and convenience, the subscript i of the auxiliary terms representing the net bottom radionuclide transport rates at the enclosure surface between the water layer and the bottom layer of the element i [Eqs. (2.4), (2.8), (2.16), and (2.18)] are not included in the general computational forms of the net bottom radionuclide transport rate into the water layer $\overline{G}_{rw,bot}$ [Eqs. (3.71), (3.72), (3.74), (3.79), and (3.82)] and the net bottom radionuclide transport rate into the bottom layer $\overline{G}_{rb,bot}$ [Eqs. (3.83a), (3.83b), and (3.83c)].

3.6 FORMULATION OF TRANSPORT SUBMODEL FOR GROUNDWATER SEEPAGE CONDITIONS

The fast-transient, one-dimensional mathematical transport model of the RADONE computer code includes a simple but physically realistic groundwater seepage flow submodel for approximately incorporating the effect of varying elevation of the groundwater table in the geographic (climatological) region on flow conditions in the main flow channel of a river or an estuary. The groundwater seepage submodel is specifically formulated to include available geophysical information about (1) average, continuous groundwater seepage flow rate into or out of the main channel, (2) porosity of the bed of the main flow channel and the ground in the vicinity of the main flow channel, and (3) temporal variation of the elevation of the groundwater table in the geographic (climatological) region of a river or an estuary.

According to the general formulation of the fast-transient, one-dimensional, two-layer, discrete-element radionuclide transport model of the RADONE computer code, every computational discrete-element equation of the governing system [Eqs. (2.1), (2.2), (2.3), (2.4), and (2.16)] includes the auxiliary term representing the groundwater seepage flow rate into the element of the channel segment. The development of the groundwater seepage flow submodel of the RADONE computer code is identical to the one included in the development of the ESTONE computer code, which is discussed in detail in its users manual [Eraslan (1983)]. Therefore, the formulation of the groundwater seepage flow submodel is only presented in summary form in this section.

In the development of the groundwater seepage flow submodel, the net groundwater seepage flow rate into the element of the main flow channel of a river or an estuary is formulated in two parts:

1. specified regional groundwater seepage flow rate, based on specified input data (Sect. 4) about temporally varying groundwater seepage flow conditions in the geographic (climatological) region of the river or estuary, and
2. hydrostatic groundwater seepage flow rate, based on specified input data about geophysical conditions of the bed of the main flow channel and the temporally varying elevation of the groundwater table, in the geographic region.

The specified regional groundwater seepage flow rate $\overline{G}_{grd,reg}$ is formulated as

$$\overline{G}_{grd,reg} = R_{grd,reg}\overline{G}_{grd,avg} \quad . \tag{3.84}$$

The two product terms of the right side of the specified regional groundwater seepage flow rate $\overline{G}_{grd,reg}$ represent the following specified conditions in the geographic (climatological) region of a river or an estuary.

1. The first product term $\overline{R}_{grd,reg}$ in Eq. (3.84) represents the temporally varying, scaling factor that determines actual regional groundwater seepage flow rate based on specified input data (Sect. 4) about groundwater seepage flow conditions.
2. The second product term $\overline{G}_{grd,avg}$ in Eq. (3.84) represents the temporally constant, average, representative value of groundwater seepage flow rate into or out of the main flow channel in each element in the form of a specified distribution (Sect. 4) along the curvilinear longitudinal x-axis of the main flow channel.

Hydrostatic groundwater seepage flow flux $\overline{g}_{grd,hwt}$, based on input data about geophysical conditions in the geographic (climatological) region of a river (or an estuary). is formulated as

$$\overline{g}_{grd,hwt} = R_{grd,por}\left[\frac{H_{grd,hwt} - \overline{H}}{H_{grd,ref}}\right]^{r_{grd}} \quad . \tag{3.85}$$

The two product terms on the right side of Eq. (3.85) represent the following effects of the geophysical conditions in the geographic (climatological) region on groundwater seepage conditions into or out of the main flow channel:

1. The first product term, which is the specified, temporally constant coefficient of composite ground porosity $R_{grd,por}$, represents the overall effect of porosity conditions of the bed of the main flow channel and the ground in the geographic region. Composite porosity conditions of the bed of the main flow channel and the ground in the vicinity of a river or an estuary generally vary along the curvilinear longitudinal x-axis of the main flow channel. Therefore, the specified, temporally constant coefficient of composite ground porosity is specified as input data (Sect. 4) for each element of the segment of the

main flow channel, based on available information about the geophysical conditions of the bed of the main flow channel and the ground in the geographic region.

2. The second product term represents the dimensionless effect of the hydrostatic pressure differential, based on the difference between (a) elevation of the water surface of the groundwater table in the geographic region and (b) elevation of the water surface in the main flow channel of a river or an estuary. Elevation of the water surface of the groundwater table is again specified as input data (Sect. 4) based on available information about groundwater table conditions in the geographic region. The specified constant $H_{grd,ref}$ [Eq. (3.85)] is an arbitrarily selected reference value of elevation (2.0 ft) associated with the water surface level of the groundwater table; it is included in the formulation strictly for convenience, for nondimensionalizing the form of the hydrostatic pressure differential. Hydrostatic groundwater seepage flow flux $\bar{g}_{grd,hwt}$ [Eq. (3.85)] is generally a complex function of the hydrostatic pressure differential in the geographic region, depending on the detailed characteristics of the microscopic structure of the porous ground. Hence, formulation of the effect of the hydrostatic pressure differential is generalized to include a power-type dependence. The power r_{grd} of the hydrostatic pressure differential is specified as a spatially varying distribution (along the curvilinear longitudinal x-axis of the main flow channel).

Hydrostatic groundwater seepage flow rate $\overline{G}_{grd,hwt}$ is evaluated by multiplying hydrostatic groundwater seepage flow flux $\bar{g}_{grd,hwt}$ [Eq. (3.85)] by the enclosure surface area of the bed contour Γ of the cross section of the main flow channel as

$$\overline{G}_{grd,hwt} = (\Delta x \Gamma)\bar{g}_{grd,hwt} \quad . \tag{3.86}$$

Hence, the net groundwater seepage flow rate $\overline{G}_{grd}$ into or out of the main flow channel of a river or an estuary is formulated as the sum of two parts: specified regional groundwater seepage flow rate $\overline{G}_{grd,reg}$ [Eq. (3.84)] and calculated hydrostatic groundwater seepage flow rate $\overline{G}_{grd,hwt}$ [Eq. (3.86)]. It is formulated as

$$\overline{G}_{grd} = \overline{G}_{grd,reg} + \overline{G}_{grd,mwt} \quad . \tag{3.87}$$

The final computational form of groundwater seepage flow rate $\overline{G}_{grd}$ [Eq. (3.87)] eliminates the auxiliary term in the system of discrete-element equations, consisting of (1) the discrete-element equation for water surface elevation [Eq. (2.1)], (2) the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)] in terms of (a) the principal solution variable, water surface elevation H, and (b) the standard geometric variable of the cross section of the main flow channel, channel bed contour Γ. All terms on both sides of the general computational form of groundwater seepage flow rate $\overline{G}_{grd}$ [Eq. (3.87)] and its two parts, (1) specified regional groundwater seepage flow rate $\overline{G}_{grd,reg}$ [Eq. (3.84)] and (2) calculated hydrostatic groundwater seepage flow rate $\overline{G}_{grd,hwt}$ [Eq. (3.86)], are evaluated at the same solution location i corresponding to the location of the element i of the segment of the main flow channel. Therefore, for brevity and convenience, the subscript i of the auxiliary terms representing groundwater seepage flow rate in element i are not included in the general computational forms of groundwater seepage flow rate $\overline{G}_{grd}$ [Eq. (3.87)] and its two parts.

The formulation of the radionuclide transport conditions, associated with the groundwater seepage flow conditions into or out of the main flow channel also requires additional information about the distribution of the net groundwater seepage flow rate $\overline{G}_{grd}$ [Eq. (3.87)] between the two layers of the channel segment, consisting of two parts as (1) the groundwater seepage flow rate into or out of the water layer in the element $\overline{G}_{grd,wl}$ [Eqs. (2.4) and (2.7)] and (2) the groundwater seepage flow rate into or out of the bottom layer in the element $\overline{G}_{grd,bl}$ [Eqs. (2.16) and (2.17)]. Considering the fact that the distribution of the groundwater seepage flow rate between the water layer and the bottom layer depends on (1) the local geometric characteristics of the element of the channel segment and (2) the characteristics of the groundwater flow in the vicinity of the element of the channel segment, the groundwater seepage flow rate, associated with the radionuclide transport conditions into or out of the two layers of the main flow channel, can be approximately but realistically formulated in terms of the net groundwater seepage flow rate into or out of the element of the main flow channel $\overline{G}_{grd}$ [Eq. (3.87)]. Hence, the groundwater seepage flow rate into or out of the water layer in the element $\overline{G}_{grd,wl}$ is approximated as equal to the net groundwater seepage flow rate into or out of the element $\overline{G}_{grd}$ [Eq. (3.87)] as

$$\overline{G}_{grd,wl} \simeq \overline{G}_{grd} \; . \tag{3.88}$$

Similarly, the groundwater seepage flow rate into or out of the bottom layer in the element $\overline{G}_{grd,bl}$ is approximated as a linearly scaled portion of the net groundwater seepage flow rate into or out of the element $\overline{G}_{grd}$ [Eq. (3.87)] as

$$\overline{G}_{grd,bl} = R_{bl,grd}\overline{G}_{grd} \; , \tag{3.89}$$

where

$R_{bl,grd}$ = specified constant bottom-layer groundwater distribution factor, for determining the groundwater seepage flow rate into or out of the bottom layer of the element of the main flow channel, associated with the radionuclide transport rate into or out of the bottom layer, according to the groundwater seepage flow conditions into or out of the main flow channel.

It is important to point out that the two separate groundwater seepage flow rates are used strictly for determining the radionuclide transport conditions into or out of the two assumed layers of the element of the main flow channel and not for the computations of the hydrodynamic conditions in the element of the main flow channel. Therefore, it is not essential to consider the mass conservation principle for water for the combined two layers, in terms of the defined groundwater seepage flow rates into or out of the two layers of the element of the main flow channel.

Hence, the assumed approximate form of the groundwater seepage flow rate into or out of the water layer in the element $\overline{G}_{grd,wl}$ [Eq. (3.88)], associated with the radionuclide transport conditions into or out of the water layer of the element of the main flow channel, eliminates the part of the auxiliary term, which includes the specified water concentration of the radionuclide in the groundwater seepage flow $\widetilde{C}_{rw,grd,wl}$ (Sect. 4), in the discrete-element equation for water concentration of the radionuclide in the water layer [Eqs. (2.4) and (2.7)], in terms of the already evaluated net groundwater seepage flow rate $\overline{G}_{grd}$ [Eq. (3.87)]. Similarly, the assumed approximate form of the groundwater seepage flow rate into or out of the bottom layer in the element $\overline{G}_{grd,bl}$ [Eq. (3.89)], associated with the radionuclide transport conditions into or out of the bottom layer of the element of the main flow channel, eliminates the part of the auxiliary term, which includes the specified bottom concentration of the radionuclide in the groundwater seepage flow $\widetilde{C}_{rb,grd,bl}$ (Sect. 4), in the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eqs. (2.16) and (2.17)] in terms of (a) the already evaluated net groundwater seepage flow

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rate $\bar{G}_{grd}$ [Eq. (3.87)] and (b) the specified constant bottom-layer groundwater distribution factor $R_{bl,grd}$ [Eq. (3.89)]. All terms on both sides of the general computational forms of (a) the groundwater seepage flow rate into or out of the water layer in the element $\bar{G}_{grd,wl}$ [Eq. (3.88)] and (b) the groundwater seepage flow rate into or out of the bottom layer in the element $\bar{G}_{grd,bl}$ [Eq. (3.89)] are evaluated at the same solution location i, corresponding to the location of element i of the segment of the main flow channel. Therefore, for brevity and convenience, the subscript i of the auxiliary terms representing groundwater seepage flow rates in element i are not included in the general computational forms of groundwater seepage flow rates $\bar{G}_{grd,wl}$ [Eq. (3.88)] and $\bar{G}_{grd,bl}$ [Eq. (3.89)].

All other auxiliary terms, representing the radionuclide transport conditions into or out of the main flow channel, associated with the groundwater seepage flow rates, are specified as input data (Sect. 4) to the RADONE computer code.

3.7 FORMULATION OF TRANSPORT SUBMODEL FOR THE WATER SURFACE

The fast-transient, one-dimensional mathematical transport model of the RADONE computer code includes all the necessary provisions for considering physically realistic mass, momentum, and radionuclide transport conditions on the water surface of a river or an estuary. In applications to site-specific problems, the computer code can incorporate all the available information as required about the climatological conditions in the geographic region of the river or estuary, consisting of the rainfall and the wind speed and direction. The development of the transport submodel for the water surface of the RADONE computer code represents a part of the detailed transport submodel for the water surface of the ESTONE computer code which is discussed in detail in its users manual [Eraslan (1983)]. Therefore, the formulation of the transport submodel for the water surface is only presented in summary form in this section.

According to the general formulation of the fast-transient, one-dimensional, two-layer, discrete-element radionuclide transport model of the RADONE computer code, the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)] include the auxiliary terms representing surface wind stress on the water surface of the upstream- and downstream-half elements, corresponding to the upstream half and downstream half, respectively, of the segment of the main flow channel.

Surface wind stress $\bar{J}'_{x,srf}$ is formulated based on a generalized empirical form, which is similar to the standard formulations of wind stress on the water surface in shallow flow regions [e.g., Hunter (1975), Dronkers (1964), Leendertse (1970), Eraslan (1983)], as

$$\bar{J}'_{x,srf} = \left\{ C_{fr,wnd} \left[\frac{\bar{\rho}_a}{\bar{\rho}_w} \right] \right\} [1 + \beta_{wnd,rnf} \bar{g}_{rnf}] [|\bar{\vec{V}}_{wnd}| (\bar{V}_{x,wnd} - \bar{V}_{x,srf})] \ . \tag{3.90}$$

The three bracketed product terms on the right side of the equation for surface wind stress [Eq. (3.90)] represent:

1. The first product term represents the effective surface friction coefficient for the air-water interface, which includes (a) the surface wind friction coefficient $C_{fr,wnd}$ (with a suggested value of 0.0026) and (b) the ratio of the density of air to the density of water, which is assumed as constant (with a suggested value of 0.0012).
2. The second product term represents the overall effect of increasing surface wind stress because of increasingly effective density of the air-water mixture in the wind under rainfall conditions.
3. The third product term represents the effect of wind speed and wind direction (along the curvilinear longitudinal x-axis of the main flow channel). It is important to note that the present empirical

formulation of surface wind stress $\overline{J}'_{x,sfr}$ [Eq. (3.90)] is based on relative surface wind velocity, which represents the difference between average channel flow velocity on the water surface (averaged over the surface width $\overline{B}_{srf}$) and the component (along the curvilinear longitudinal x-axis of the main flow channel) of actual wind velocity $\overline{V}_{x,wnd}$. Average channel flow velocity on the water surface is determined according to the general formulation of the self-similar vertical and lateral variations of channel flow velocity $V_x(y,\eta)$ [Eqs. (3.31a) and (3.31b)] as

$$\overline{V}_{x,srf} = \frac{(n+1)}{n}\frac{\overline{D}}{\overline{B}_{srf}\langle D^2\rangle}\overline{G}_x = \frac{(n+1)}{n}\frac{\overline{D}^2}{\langle D^2\rangle}\overline{V}_x \quad , \tag{3.91}$$

which includes the second mean-integral moment of depth $\langle D^2\rangle$ [Eq. (3.32)].

The final computational form of surface wind stress $\overline{J}'_{x,srf}$ [Eq. (3.90)] eliminates the auxiliary terms of the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)] in terms of the principal solution variable, channel flow rate $\overline{G}_x$ and standard geometric variables of the cross section of the main flow channel. All terms on both sides of the general computational form of surface wind stress $\overline{J}'_{x,srf}$ [Eqs. (3.90) and (3.91)] are evaluated at the same solution locations, at the location of the upstream half-element $i - 1/4$ and the downstream half-element $i + 1/4$, corresponding to the locations of the upstream half and the downstream half, respectively, of the segment of the main flow channel. Therefore, for brevity and convenience, the subscripts $i - 1/4$ and $i + 1/4$ are not included in the formulation of surface wind stress $\overline{J}'_{x,srf}$ [Eqs. (3.90) and (3.91)].

All other auxiliary terms representing the mass momentum and radionuclide transport conditions, associated with the rainfall and wind conditions on the water surface of the main flow channel are specified as input data (Sect. 4) to the RADONE computer code.

3.8 FORMULATION OF RADIOLOGICAL DECAY RATES

The fast-transient, one-dimensional mathematical model of the RADONE computer code includes the radiological decay effects in the water layer and in the bottom layer of the main flow channel as formulations based on first-order radiological rates.

Hence, the radiological decay rate of the water concentration of the radionuclide in the water layer $\dot{\overline{C}}_{rw}$ is formulated as

$$\dot{\overline{C}}_{rw} = -r_{nuc}\overline{C}_{rw} \quad , \tag{3.92a}$$

and the radiological decay rate of the bottom concentration of the radionuclide in the bottom layer $\dot{\overline{C}}_{rb}$ is formulated as

$$\dot{\overline{C}}_{rb} = -r_{nuc}\overline{C}_{rb} \quad , \tag{3.92b}$$

where the nuclear decay rate coefficient r_{nuc} is determined based on the specified half-life of the radionuclide $t^{1/2}_{nuc}$ as

$$r_{nuc} = \frac{\ln 2}{t_{1/2,nuc}} \simeq \frac{0.6931}{t_{1/2,nuc}} \quad . \tag{3.93}$$

The final computational forms of the radiological decay rate of the water concentration of the radionuclide in the water layer $\overleftarrow{C}_{rw}$ [Eq. (3.92a)] and the radiological decay rate of the bottom concentration of the radionuclide in the bottom layer $\overleftarrow{C}_{rb}$ [Eq. (3.92b)] eliminate the auxiliary terms of (1) the discrete-element equation for water concentration of the radionuclide in the water layer [Eqs. (2.4) and (2.12)] and (2) the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eqs. (2.16) and (2.21)], respectively. The values for the water concentration of the radionuclide in the water layer $\overleftarrow{C}_{rw}$ in Eq. (3.92a) and the bottom concentration of the radionuclide in the bottom layer $\overleftarrow{C}_{rb}$ in Eq. (3.92b) are evaluated at the same solution location *i* corresponding to the location of element *i* of the segment of the main flow channel. Therefore, for brevity and convenience, the subscript *i* of the auxiliary terms representing the radiological decay rates in element *i* are not included in the general computational forms of the radiological decay rate of the water concentration of the radionuclide in the water layer $\overleftarrow{C}_{rw}$ [Eq. (3.92a)] and the radiological decay rate of the bottom concentration of the radionuclide in the bottom layer $\overleftarrow{C}_{rb}$ [Eq. (3.92b)].

4. SUMMARY OF SPECIFIED TRANSPORT CONDITIONS

The mathematical model of RADONE computer code includes all necessary computational capabilities for accurately specifying, based on all available site-specific information, the temporal and spatial variations of mass, momentum, and radionuclide transport conditions across the boundary enclosure surfaces of the main flow channel of a river or an estuary. These boundary enclosure surfaces consist of (1) upstream-end and downstream-end enclosure surfaces, (2) the water surface, (3) the enclosure surface of the channel bed, (4) enclosure surfaces associated with connected streams or tributaries, and (5) intake and discharge enclosure surfaces of power plants.

Temporal variations of transport conditions across the boundary enclosure surfaces of the main flow channel are specifically formulated to incorporate both short- and long-term variations of (1) climatological and geophysical conditions in the geographic region and (2) power plant operational conditions that collectively control the hydrodynamic and radionuclide concentration conditions in a river or an estuary. The necessary input data for the temporal variations of the transport conditions can be specified in two types of format which can be used separately or collectively in formulating specified transport rates across the boundary enclosure surfaces of the main flow channel.

The first type of format for input data considers specified conditions on the boundary enclosure surfaces that remain uniform during arbitrarily specified time periods. This type of format allows the user of the RADONE computer code to utilize temporally averaged data, including (1) hourly averaged conditions (or shorter time periods), (2) daily averaged conditions, (3) weekly averaged conditions, and (4) conditions averaged over any arbitrarily specified time period. These data can be obtained from available information about site-specific climatological, geophysical, and plant operational conditions in the geographic region of a river or an estuary. Specified averaged conditions are assumed to remain uniform during the arbitrarily specified time periods; hence, this type of data format, in a sense, represents the first term of a special Fourier cosine series expansion of any temporally varying condition on a boundary enclosure surface of the main flow channel. Since the durations of specified time periods can be selected arbitrarily with possibly different durations for the different periods, this type of format for averaged conditions can be used to incorporate available site-specific information with different levels of temporal resolution for different specified time periods.

The second type of format for input data considers harmonic variations of specified conditions on the boundary enclosure surfaces with arbitrarily specified periods, amplitudes, and lag times (relative to midnight) based on available information about site-specific climatological and geophysical conditions in the geographic region of a river or an estuary. This type of data format, in a sense, represents the higher order terms of a special Fourier cosine series expansion of any temporally varying condition on a boundary enclosure surface of the main flow channel. The harmonic format of specified input data enables the user to incorporate temporally continuous, periodic conditions, based on specified periods, amplitudes, and lag times, for any specified condition associated with mass, momentum, and radionuclide transport across any boundary enclosure surface of the main flow of a river or an estuary.

Hence, the general formulation of the mathematical model of the RADONE computer code enables the user to simulate the hydrodynamic and radionuclide concentration conditions in a river or an estuary with any level of temporal resolution of available information about the climatological, geophysical, and plant operational conditions specified on the boundary enclosure surfaces of the main flow channel.

Specified spatial variations of transport conditions across the boundary enclosure surfaces of the main flow channel are incorporated in the form of specified conditions at the locations of (1) elements that correspond to the locations of the centers of arbitrarily specified channel segments and (2) upstream and/or downstream enclosure surfaces of elements that correspond to the locations of the upstream and/or downstream enclosure cross sections of specified channel segments. Since the sizes of elements of the main flow channel can be selected arbitrarily, the spatial variations of the climatological, geophysical, and plant operational conditions, which determine specified transport conditions on the boundary enclosure surfaces of the main flow channel, can be incorporated with any desired level of spatial accuracy in applications of the RADONE computer code to the simulation of hydrodynamic and radionuclide concentration conditions in a river or an estuary.

4.1 ADDITIONAL DEFINITIONS OF MATHEMATICAL VARIABLES ASSOCIATED WITH SPECIFIED TRANSPORT CONDITIONS

The additional auxiliary variables of the fast-transient, one-dimensional, two-layer discrete-element mathematical model of the RADONE computer code that are used in the formulations of the temporal and spatial variations of the mass, momentum, and radionuclide transport conditions at the boundary enclosure surfaces of the main flow channel of a river or an estuary are:

$C_{rb,avg;dns,p}$ = specified input data for downstream-end average bottom concentration of the radionuclide in the bottom layer, for specified time period $\Delta t_{dns,p}$, used to represent the long-term variation of the mean value of the bottom concentration of the radionuclide in the bottom layer (excluding harmonic variations) in the downstream coastal open end of the main flow channel [Eq. (4.33), radiologic unit/ft^3];

$C_{rb,avg;ups,p}$ = specified input data for upstream-end average bottom concentration of the radionuclide in the bottom layer, for specified time period $\Delta t_{ups,p}$, used to represent the long-term variation of the mean value of the bottom concentration of the radionuclide in the bottom layer (excluding harmonic variations) in the upstream coastal open end of the main flow channel [Eq. (4.32), radiologic unit/ft^3];

$\bar{C}_{rb,dis,m}$ = specified value of the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant m [Eqs. (4.111) and (4.112), radiologic unit/ft^3];

$C_{rb,dis,m,p}$ = specified input data for the bottom concentration of the radionuclide associated with the discharge flow, for specified time period $\Delta t_{plt,m,p}$, of plant m [Eqs. (4.109) and (4.111), radiologic unit/ft^3];

$\bar{C}_{rb;dns}$ = specified (or calculated based on specified input data) downstream-end bottom concentration of the radionuclide in the bottom layer at the downstream-end boundary enclosure surface of the main flow channel [Eqs. (4.11), (4.23), (4.33), (4.37a), (4.37b), and (4.37c), radiologic unit/ft^3];

$C_{rb;dns,p}$ = specified input data for downstream-end bottom concentration of the radionuclide in the bottom layer at the downstream-end boundary enclosure surface of the main flow channel, for specified time period $\Delta t_{dns,p}$ [Eq. (4.23), radiologic unit/ft^3];

$C_{rb,grd,bl,p}$ = specified input data for the bottom concentration of the radionuclide in the groundwater seepage flow, into the bottom layer of the main flow channel, for specified time period $\Delta t_{grd,p}$ [Eq. (4.64), radiologic unit/ft^3];

$\bar{C}_{rb,int,m}$ = specified value of the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant m [Eqs. (4.96) and (4.98), radiologic unit/ft^3];

$C_{rb,int,m,p}$ = specified input data for the bottom concentration of the radionuclide, associated with the intake flow, for specified time period $\Delta t_{plt,m,p}$, of plant m [Eq. (4.96), radiologic unit/ft^3];

$C_{rb,\max;dns}$ = specified input data for approximate maximum value of the bottom concentration of the radionuclide in the bottom layer at the downstream coastal open end of the main flow channel [Eq. (4.37c), radiologic unit/ft^3];

$C_{rb,\max;ups}$ = specified input data for approximate maximum value of the bottom concentration of the radionuclide in the bottom layer at the upstream coastal open end of the main flow channel [Eq. (4.36c), radiologic unit/ft^3];

$C_{rb,\min;dns}$ = specified input data for approximate minimum value of the bottom concentration of the radionuclide in the bottom layer at the downstream coastal open end of the main flow channel [Eq. (4.37b), radiologic unit/ft^3];

$C_{rb,\min;ups}$ = specified input data for approximate minimum value of the bottom concentration of the radionuclide in the bottom layer at the upstream coastal open end of the main flow channel [Eq. (4.36c), radiologic unit/ft^3];

$C_{rb,srm,n,bl,p}$ = specified input data for the bottom concentration of the radionuclide in the flow of stream of tributary n, into the bottom layer of the main flow channel, for specified time period $\Delta t_{srm,n,p}$ [Eq. (4.71), radiologic unit/ft^3];

$\bar{C}_{rb;ups}$ = specified (or calculated based on specified input data) upstream-end bottom concentration of the radionuclide in the bottom layer at the upstream-end boundary enclosure surface of the main flow channel [Eqs. (4.10), (4.22), (4.32), (4.36a), (4.36b), and (4.36c), radiologic unit/ft^3];

$C_{rb;ups,p}$ = specified input data for upstream-end bottom concentration of the radionuclide in the bottom layer at the upstream-end boundary enclosure surface of the main flow channel, for specified time period $\Delta t_{ups,p}$ [Eq. (4.22), radiologic unit/ft^3];

$C_{rnf,wnd}$ = specified constant for calculating approximate rainfall velocity (along the curvilinear longitudinal x-axis of the main flow channel) at the water surface as a percentage of wind velocity (along the curvilinear longitudinal x-axis of the main flow channel) at the location of the center of element i of the main flow channel [Eq. (4.49), suggested value is 0.4];

$C_{rw,avg;dns,p}$ = specified input data for downstream-end average water concentration of the radionuclide in the water layer, for specified time period $\Delta t_{dns,p}$, used to represent the long-term variation of the mean value of the water concentration of the radionuclide in the water layer (excluding harmonic variations) in the downstream coastal open end of the main flow channel [Eq. (4.31), radiologic unit/ft^3];

$C_{rw,avg;ups,p}$ = specified input data for upstream-end average water concentration of the radionuclide in the water layer, for specified time period $\Delta t_{ups,p}$, used to represent the long-term variation of the mean value of the water concentration of the radionuclide in the water layer (excluding harmonic variations) in the upstream coastal open end of the main flow channel [Eq. (4.30), radiologic unit/ft^3];

$\bar{C}_{rw,dis,m}$ = specified value of the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant m [Eqs. (4.106) and (4.107), radiologic unit/ft^3];

$C_{rw,dis,m,p}$ = specified input data for the water concentration of the radionuclide, associated with the discharge flow, for specified time period $\Delta t_{plt,m,p}$, of plant m [Eqs. (4.104) and (4.106), radiologic unit/ft^3];

$\bar{C}_{rw;dns}$ = specified (or calculated based on specified input data) downstream-end water concentration of the radionuclide in the water layer at the downstream-end boundary enclosure surface of the main flow channel [Eqs. (4.9), (4.11), (4.21), (4.31), (4.35a), (4.35b), and (4.35c), radiologic unit/ft^3];

$C_{rw;dns,p}$ = specified input data for downstream-end water concentration of the radionuclide in the water layer at the downstream-end boundary enclosure surface of the main flow channel, for specified time period $\Delta t_{dns,p}$ [Eq. (4.21), radiologic unit/ft^3];

$C_{rw,grd,wl,p}$ = specified input data for the water concentration of the radionuclide in the groundwater seepage flow, into the water layer of the main flow channel for specified time period $\Delta t_{grd,p}$ [Eq. (4.63), radiologic unit/ft^3];

$\bar{C}_{rw,int,D,m;i}$ = vertically local water concentration of the radionuclide in the water layer at the specified depth of the intake of plant m, based on specific input data about the location of the intake structure and the water concentration of the radionuclide in the water layer in the intake element $i = i_{int,m}$ of the main flow channel [Eqs. (4.91) and (4.93a), radiologic unit/ft^3];

$\bar{C}_{rw,int,m}$ = specified value of the water concentration of the radionuclide of the intake flow, withdrawn from the water layer, into the intake structure of plant m [Eqs. (4.90) and (4.94), radiologic unit/ft^3];

$C_{rw,int,m,p}$ = specified input data for the water concentration of the radionuclide, associated with the intake flow, for specified time period $\Delta t_{plt,m}$, of plant m [Eq. (4.90), radiologic unit/ft^3];

$C_{rw,\max;dns}$ = specified input data for approximate maximum value of the water concentration of the radionuclide in the water layer at the downstream coastal open end of the main flow channel [Eq. (4.35c), radiologic unit/ft^3];

$C_{rw,\max;ups}$ = specified input data for approximate maximum value of the water concentration of the radionuclide in the water layer at the upstream coastal open end of the main flow channel [Eq. (4.34c), radiologic unit/ft^3];

$C_{rw,\min;dns}$ = specified input data for approximate minimum value of the water concentration of the radionuclide in the water layer at the downstream coastal open end of the main flow channel [Eq. (4.35b), radiologic unit/ft^3];

$C_{rw,\min;ups}$ = specified input data for approximate minimum value of the water concentration of the radionuclide in the water layer at the upstream coastal open end of the main flow channel [Eq. (4.34b), radiologic unit/ft^3];

$C_{rw,rnf,avg,p}$ = specified input data for average water concentration of the radionuclide in the rainfall, in the geographic (climatological) region of the main flow channel, for specified time period $\Delta t_{srf,p}$ [Eq. (4.53), radiologic unit/ft^3];

$C_{rw,srm,n,wl,p}$ = specified input data for the water concentration of the radionuclide in the flow of stream or tributary n, into the water layer of the main flow channel, for specified time period $\Delta t_{srm,n,p}$ [Eq. (4.70), radiologic unit/ft^3];

$\bar{C}_{rw;ups}$ = specified (or calculated based on specified input data) upstream-end water concentration of the radionuclide in the water layer at the upstream-end boundary enclosure surface of the main flow channel [Eqs. (4.8), (4.20), (4.30), (4.34a), (4.34b), and (4.34c), radiologic unit/ft^3];

$C_{rw;ups,p}$ = specified input data for upstream-end water concentration of the radionuclide in the water layer at the upstream-end boundary enclosure surface of the main flow channel, for specified time period $\Delta t_{ups,p}$ [Eq. (4.20), radiologic unit/ft^3];

$\overline{D}_{bot,int,m}$ = specified input data for the temporally constant depth of the bottom of the main flow channel at the location of the intake of power plant m along the main flow channel [Eqs. (4.75), (4.91), (4.92), and (4.93b), ft];

$\overline{D}_{int,m}$ = specified input data for the temporally constant depth of the intake of power plant m in the main flow channel [Eqs. (4.74) and (4.92), ft];

dns,N = specified input data for the number of tidal harmonics (maximum of eight) of the downstream-end tidal variation of water surface elevation a the downstream coastal open end of the main flow channel [Eq. (4.25)];

dns,n = index of the tidal harmonics of the downstream-end tidal variation of water surface elevation at the downstream coastal open end of the main flow channel [Eq. (4.25)];

$G_{dis,m,p}$ = specified input data for the discharge flow rate of plant m into the main flow channel, for specified time period $\Delta t_{plt,m,p}$ [Eq. (4.99), ft^3/h];

$\overline{G}_{grd,avg;i}$ = specified input data for temporally constant average groundwater seepage flow rate into or out of element i of the main flow channel [Eqs. (3.84) and (4.58), ft^3/h];

$G_{int,m,p}$ = specified input data for the intake flow rate of plant m into or out of the main flow channel, for specified time period $\Delta t_{plt,m,p}$ [Eq. (4.83), ft^3/h];

$\overline{G}_{rw,x;dns}$ = calculated (based on specified input data) downstream-end nonconvective (convection-defect and eddy-turbulent) radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) at the downstream-end boundary enclosure surface of the main flow channel [Eq. (4.15), radiologic unit/h, generally negligible];

$\overline{G}_{rw,x;ups}$ = calculated (based on specified input data) upstream-end nonconvective (convection-defect and eddy-turbulent) radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) at the upstream-end boundary enclosure surface of the main flow channel [Eq. (4.14), radiologic unit/h, generally negligible];

$G_{srm,n,p}$ = specified input data for the flow rate of stream or tributary n into or out of the main flow channel, for the specified time period $\Delta t_{srm,n,p}$ [Eq. (4.68), ft^3/h];

$\overline{G}_{x;dns}$ = specified (or calculated based on specified input data) downstream-end channel flow at the downstream-end boundary enclosure surface of the main flow channel [Eqs. (4.6), (4.18), and (4.27), ft^3/h];

$\overline{G}'_{x;dns}$ = calculated (based on specified input data) downstream-end nonconvective (convection-defect) momentum transport rate (along the curvilinear longitudinal x-axis of the main flow channel) at the downstream-end boundary enclosure surface of the main flow channel [Eq. (4.13), ft^4/h, generally negligible];

$G_{x;dns,p}$ = specified input data for downstream-end channel flow rate at the downstream-end boundary enclosure surface of the main flow channel, for the specified time period $\Delta t_{dns,p}$ [Eq. (4.18), ft^3/h];

$G_{x;i-\frac{1}{4},p}$ = optional specified input data for channel flow rate in the upstream half-element $i - \frac{1}{4}$, for the specified constant time period $\Delta t_{hyd,p}$; used for special option applications that exclude the solution of hydrodynamic conditions in the main flow channel [Eq. (4.116a), ft^3/h];

$G_{x,i+¼,p}$ = optional specified input data for channel flow rate in the downstream half-element $i + ¼$, for the specified constant time period $\Delta t_{hyd,p}$; used for special option applications that exclude the solution of hydrodynamic conditions in the main flow channel [Eq. (4.116b), ft^3/h];

$\overline{G}_{x;ups}$ = specified (or calculated based on specified input data) upstream-end channel flow rate at the upstream-end boundary enclosure surface of the main flow channel [Eqs. (4.4), (4.16), and (4.26), ft^3/h];

$\overline{G}^{*\prime}_{x,ups}$ = calculated (based on specified input data) upstream-end nonconvective (convection-defect) momentum transport rate (along the curvilinear longitudinal x-axis of the main flow channel) at the upstream-end boundary enclosure surface of the main flow channel [Eq. (4.12), ft^4/h];

$G_{x;ups,p}$ = specified input data for upstream-end channel flow rate at the upstream-end boundary enclosure surface of the main flow channel for the specified time period $\Delta t_{ups,p}$ [Eq. (4.16), ft^3/h];

$\overline{g}_{rnf,avg,p}$ = specified input data for average rainfall rate (per unit area) in the geographic (climatological) region of the main flow channel, for specified time period $\Delta t_{srf,p}$ [Eq. (4.44), ft/h];

$\overline{H}_{dns}$ = based on specified input data, the specified (or calculated) downstream-end water surface elevation at the downstream-end boundary enclosure surface of the main flow channel [Eqs. (4.3) and (4.25)];

$H_{grd,mwt;i}$ = specified input data for temporally constant average mean water surface elevation in the groundwater table (relative to the arbitrarily specified level associated with water surface elevation) for element i of the main flow channel [Eqs. (4.56) and (4.61), ft];

$\overline{H}_{i,p}$ = optional specified input data for water surface elevation in element i, for specified time period $\Delta t_{hyd,p}$; used for special option applications that exclude the solution of the hydrodynamic conditions in the main flow channel [Eqs. (4.113) and (4.115), ft];

$\overline{H}_{mwl;dns}$ = specified input data for constant downstream-end mean water surface elevation (mean water level), representing the long-term constant average value of water surface elevation at the downstream coastal open end of the main flow channel [Eq. (4.25), ft];

$\overline{H}_{mwl;ups}$ = specified input data for constant upstream-end mean water surface elevation (mean water level), representing the long-term constant average value of water surface elevation at the upstream coastal open end of the main flow channel [Eq. (4.24), ft];

$H_{tid;dns,n}$ = specified input data for the amplitude of the nth tidal harmonic of the downstream-end tidal variation of water surface elevation at the downstream coastal open end of the main flow channel [Eq. (4.25), ft];

$H_{tid;ups,n}$ = specified input data for the amplitude of the nth tidal harmonic of the upstream-end tidal variation of water surface elevation at the upstream coastal open end of the main flow channel [Eq. (4.24), ft];

H_{ups} = specified (or calculated based on specified input data) upstream-end water surface elevation at the upstream-end enclosure surface of the main flow channel [Eqs. (4.2) and (4.24), ft];

$i_{dis,m}$ = specified input data for the element containing the discharge of power plant m along the curvilinear longitudinal x-axis of the main flow channel [Eq. (4.73)];

$i_{int,m}$ = specified input data for the element containing the intake of power plant m along the curvilinear longitudinal x-axis of the main flow channel [Eq. (4.72)];

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$i_{srm,n}$ = specified input data for the element containing the connecting junction of stream or tributary n, along the curvilinear longitudinal x-axis of the main flow channel [Eq. (4.65)];

$J_{opr,m}$ = temporally varying integer control parameter for the operational condition of power plant m [Eq. (4.82)];

= 0 if power plant m is not operating,
= 1 if power plant m is operating;

$J_{opr,m,p}$ = specified input data for the integer control parameter for the operational condition of power plant m, for specified time period $\Delta t_{plt,m,p}$ [Eq. (4.82)];

$J_{rb,dis,m}$ = integer control parameter for determining the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant m [Eqs. (4.108), (4.109), and (4.111)],

= 0 if the bottom concentration of the radionuclide in the discharge flow is internally calculated based on (1) actual upwind-differenced value of the bottom concentration of the radionuclide in the intake flow $\widetilde{C}_{rb,int,m,bl;i}$ of plant m [Eq. (4.97)], (2) specified radionuclide concentration rise $\overline{\Delta C}_{rb,plt,m}$ that occurs in plant m [Eq. (4.109)], and (3) specified constant coefficient $k_{rb,dis,m}$ for controlling the bottom concentration of the radionuclide in the discharge flow of plant m [Eq. (4.81)],

= 1 if the bottom concentration of the radionuclide in the discharge flow is determined based on specified input data for the temporal variation of the bottom concentration of the radionuclide associated with the discharge flow $C_{rb,dis,m,p}$, for specified time period $\Delta t_{plt,m,p}$, of plant m [Eq. (4.111)];

$J_{rb,dis,m,p}$ = specified input data for the integer control parameter for determining the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant m, for specified time period $\Delta t_{plt,m,p}$ [Eq. (4.108)];

$J_{rb,int,m}$ = integer control parameter for determining the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant m [Eq. (4.95)],

= 0 if the bottom concentration of the radionuclide in the intake flow is internally calculated based on (1) the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element $i = i_{int,m}$, which contains the intake of plant m, and (2) the specified constant coefficient $k_{rb,int,m}$ for controlling the bottom concentration of the radionuclide in the intake flow of plant m [Eq. (4.97)],

= 1 if the bottom concentration of the radionuclide in the intake flow is determined based on specified input data for the temporal variation of the bottom concentration of the radionuclide associated with the intake flow $C_{rb,int,m,p}$, for specified time period $\Delta t_{plt,m,p}$, of plant m [Eq. (4.98)];

$J_{rb,int,m,p}$ = specified input data for the integer control parameter for determining the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant m, for specified time period $\Delta t_{plt,m,p}$ [Eq. (4.95)];

$J_{rb,srm,n,bl}$ = specified input data for temporally constant integer control parameter for determining the bottom concentration of the radionuclide in the flow of stream or tributary n into the main flow channel [Eq. (4.67)],

= 0 if the bottom concentration of the radionuclide in the flow of stream or tributary n is determined as the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in the element of the junction $i = i_{srm,n}$ of stream or tributary n,

= 1 if the bottom concentration of the radionuclide in the flow of stream or tributary n is determined based on specified input data for the temporal variation of the bottom concentration of the radionuclide $C_{rb,srm,n,bl,p}$ in the flow of stream or tributary n, for specified time period $\Delta t_{srm,n,p}$ [Eq. (4.71)];

$J_{rw,dis,m}$ = integer control parameter for determining the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant m [Eqs. (4.103), (4.104), and (4.106)],

= 0 if the water concentration of the radionuclide in the discharge flow is internally calculated based on (1) actual upwind-differenced value of the water concentration of the radionuclide in the intake flow $\widetilde{C}_{rw,int,m,wl}$ of plant m [Eqs. (4.93a) and (4.93b)], (2) specified radionuclide concentration rise $\overline{\Delta C}_{rw,plt,m}$ that occurs in plant m [Eqs. (4.104) and (4.105)], and (3) specified constant coefficient $k_{rw,dis,m}$ for controlling the water concentration of the radionuclide in the discharge flow of plant m [Eq. (4.80)],

= 1 if the water concentration of the radionuclide in the discharge flow is determined based on specified input data for the temporal variation of the water concentration of the radionuclide associated with the discharge flow $C_{rw,dis,m,p}$, for specified time period $\Delta t_{plt,m,p}$, of plant m [Eq. (4.106)];

$J_{rw,dis,m,p}$ = specified input data for the integer control parameter for determining the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant m, for specified time period $\Delta t_{plt,m,p}$ [Eq. (4.106)];

$J_{rw,int,m}$ = integer control parameter for determining the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant m [Eq. (4.89)],

= 0 if the water concentration of the radionuclide in the intake flow is internally calculated based on (1) the water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element $i = i_{int,m}$, which contains the intake of plant m, (2) vertically local water concentration of the radionuclide in the water layer at the location of the intake structure $\overline{C}_{rw,int,D,m,wl;i}$ [Eq. (4.91)] of plant m, and (3) the specified constant coefficient $k_{rw,int,m}$ for controlling the water concentration of the radionuclide in the intake flow of plant m [Eq. (4.77)],

= 1 if the water concentration of the radionuclide in the intake flow is determined based on specified input data for the temporal variation of the water concentration of the radionuclide associated with the intake flow $C_{rw,int,m,p}$, for specified time period $\Delta t_{plt,m,p}$ [Eq. (4.90)];

$J_{rw,int,m,p}$ = specified input data for the integer control parameter for specifying the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant m, for specified time period $\Delta t_{plt,m,p}$ [Eq. (4.89)];

$J_{rw,srm,n,wl}$ = specified input data for temporally constant integer control parameter for determining the water concentration of the radionuclide in the flow of stream or tributary n into the main flow channel [Eq. (4.66)],

= 0 if the water concentration of the radionuclide in the flow of stream or tributary n is determined as the water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in the element of the junction $i = i_{srm,n}$ of stream or tributary n,

= 1 if the water concentration of the radionuclide in the flow of stream or tributary n is determined based on specified input data for the temporal variation of the water concentration of the radionuclide $C_{rw,srm,n,wl,p}$ in the flow of stream or tributary n, for specified time period $\Delta t_{srm,n,p}$ [Eq. (4.70)];

$k_{rb,dis,m}$ = specified constant coefficient for controlling the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant m, representing the factor required for approximately considering the effects of the design and structural features of the discharge of plant m on the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure in the element $i = i_{dis,m}$, which contains the discharge of plant m [Eqs. (4.81), (4.110), and (4.112)];

$k_{rb,int,m}$ = specified constant coefficient for controlling the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant m, representing the factor required for determining the effect of the vertical location of the intake structure relative to the bottom layer, on the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure, in the element $i = i_{int,m}$, which contains the intake of plant m [Eqs. (4.78) and (4.97)];

$k_{rw,dis,m}$ = specified constant coefficient for controlling the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant m, representing the factor required for approximately considering the effects of the design and structural feature of the discharge of plant m on the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure, in the element $i = i_{dis,m}$, which contains the discharge of plant m [Eqs. (4.80), (4.105), and (4.107)];

$k_{rw,int,m}$ = specified constant coefficient for controlling the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant m, representing the factor required for determining the effect of the vertical location of the intake structure, relative to the water layer, on the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure, in the element $i = i_{int,m}$, which contains the intake of plant m [Eqs. (4.77), (4.93a), and (4.93b)];

N_{plt} = specified input data for the number of power plants along the curvilinear longitudinal x-axis of the main flow channel;

N_{srm} = specified input data for the number of stream or tributary junctions along the curvilinear longitudinal x-axis of the main flow channel;

$R_{bl,grd;i}$ = specified, temporally constant bottom-layer groundwater distribution (along the curvilinear longitudinal x-axis of the main flow channel) factor for determining the groundwater seepage flow rate into or out of the bottom layer of element i of the main flow channel, associated with the radionuclide transport rate into or out of the bottom layer, according to the groundwater seepage flow rate into or out of the main flow channel [Eqs. (3.89) and (4.59)];

$R_{grd,por;i}$ = specified input data for the temporally constant coefficient of composite ground porosity, associated with the formulation of hydrostatic groundwater seepage flux into or out of element i of the main flow channel [Eqs. (3.85) and (4.55), ft/h];

$R_{grd,reg,p}$ = specified input data for the scaling factor associated with determining the temporal variation of regional groundwater seepage flow rate into or out of the main flow channel, for the specified time period $\Delta t_{grd,p}$ [Eqs. (3.84) and (4.60)];

$R_{wl,dis,m}$ = specified input data for constant factor for controlling the discharge flow into the water layer for plant m, representing the portion (as percent) of the discharge flow rate, discharged into the water layer, from the discharge structure, in the element $i = i_{dis,m}$, which contains the discharge of plant m [Eqs. (4.79), (4.101), and (4.102)];

$R_{wl,int,m}$ = specified input data for constant factor for controlling the intake flow from the water layer for plant m, representing the portion (as percent) of the intake flow rate, withdrawn from the water layer, into the intake structure, in the element $i = i_{int,m}$, which contains the intake of plant m [Eqs. (4.76), (4.87), and (4.88)];

$r_{grd;i}$ = specified input data for the temporally constant power of the hydrostatic pressure gradient, associated with the formulation of hydrostatic groundwater seepage flux into or out of element i of the main flow channel [Eqs. (3.85) and (4.57)];

srf,N = specified input data for the number of harmonics (maximum of two) for representing short-term variations of the climatological conditions above the water surface in the geographic (climatological) region of the main flow channel [Eqs. (4.44)–(4.46) and (4.53)];

srf,n = index of the harmonics for representing short-term variations of the climatological conditions above the water surface in the geographic (climatological) region of the main flow channel [Eqs. (4.44)–(4.46) and (4.53)];

$t_{dns,p}$ = beginning time for specified time period $\Delta t_{dns,p}$ of the specified input data for flow conditions at the downstream-end boundary enclosure surface of the main flow channel [Eqs. (4.19), (4.21), (4.23), (4.25), (4.31), and (4.33), hour of the day associated with the time of calculations];

$t_{dns,p+1}$ = ending time of specified time period $\Delta t_{dns,p}$ of the specified input data for flow conditions at the downstream-end boundary enclosure surface of the main flow channel [Eqs. (4.19), (4.21), (4.23), (4.25), (4.31), and (4.33), hour of the day associated with the time of calculations];

$t_{grd,p}$ = beginning time of specified time period $\Delta t_{grd,p}$ of the specified input data for groundwater seepage flow conditions in the geographic (climatological) regions of the main flow channel [Eqs. (4.60), (4.61), (4.63), and (4.64), hour of the day associated with the time of calculations];

$t_{grd,p+1}$ = ending time of specified time period $\Delta t_{grd,p}$ of the specified input data for groundwater seepage flow conditions in the geographic (climatological) regions of the main flow channel

[Eqs. (4.60), (4.61), (4.63), and (4.64), hour of the day associated with the time of calculations];

$t_{hyd,p}$ = beginning time of specified constant time period Δt_{hyd} of the optional specified input data for hydrodynamic conditions; used for special option applications that exclude the solution of hydrodynamic conditions in the main flow channel [Eqs. (4.113) through (4.116b), hour of the day associated with the time of calculations];

$t_{hyd,p+1}$ = ending time of specified constant time period Δt_{hyd} of the optional specified input data for hydrodynamic conditions; used for special option applications that exclude the solution of hydrodynamic conditions in the main flow channel [Eqs. (4.115), (4.116a), and (4.116b), hour of the day associated with the time of calculations];

$t_{lag,dns,n}$ = specified input data for the lag time of the *n*th tidal harmonic of the downstream-end tidal variation of water surface elevation at the downstream coastal open end of the main flow channel [Eq. (4.25), hour of the day relative to midnight];

$t_{lag,rnf,p,n}$ = specified input data for the lag time of the *n*th harmonic of the difference in rainfall rate (per unit area), for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of rainfall rate from the specified average rainfall rate during specified time period $\Delta t_{srf,p}$ in the geographic (climatological) region of the main flow channel [Eq. (4.44), hour of the day relative to midnight];

$t_{lag,rw,rnf,p,n}$ = specified input data for the lag time of the *n*th harmonic of the difference in water concentration of the radionuclide in the rainfall, for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of the water concentration in the rainfall from the specified average water concentration in the rainfall during the specified time period $\Delta t_{srf,p}$, in the geographic (climatological) region of the main flow channel [Eq. (4.53), hour of the day relative to midnight];

$t_{lag,ups,n}$ = specified input data for the lag time of the *n*th tidal harmonic of the upstream-end tidal variation of water surface elevation at the upstream coastal open end of the main flow channel [Eq. (4.24), hour of the day relative to midnight];

$t_{lag,wnd,p,n}$ = specified input data for the lag time of the *n*th harmonic of the difference in wind speed, for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of wind speed from the specified average wind speed during specified time period $\Delta t_{srf,p}$ in the geographic (climatological) region of the main flow channel [Eq. (4.45), hour of the day relative to midnight];

$t_{lag,wnd,ref,p,n}$ = specified input data for the lag time of the *n*th harmonic of the difference in wind direction (relative to an arbitrarily specified geographic reference coordinate system), for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of wind direction from the specified average wind direction during specified time period $\Delta t_{srf,p}$ in the geographic (climatological) region of the main flow channel [Eq. (4.46), hour of the day relative to midnight];

$t_{plt,m,p}$ = beginning time of specified time period $\Delta t_{plt,m,p}$ of the specified input data for the operational conditions of plant *m* associated with the conditions of intake and discharge flows of the power plant into or out of the main flow channel [Eqs. (4.19), (4.21), (4.23), (4.25), (4.31), (4.33), (4.82)–(4.86), (4.89), (4.90) (4.94)–(4.96), (4.99), (4.100), (4.103), (4.104), (4.106), (4.108), (4.109), and (4.111), hour of the day associated with the time calculations];

$t_{plt,m,p+1}$ = ending time of specified time period $\Delta t_{plt,m,p}$, of the specified input data for the operational conditions of plant m associated with the conditions of intake and discharge flows of the power plant into or out of the main flow channel [Eqs. (4.19), (4.21), (4.23), (4.25), (4.31), (4.33), (4.82)–(4.86), (4.89), (4.90), (4.94)–(4.96), (4.99), (4.100), (4.103), (4.104), (4.106), (4.108), (4.109), and (4.111), hour of the day associated with the time calculations];

$t_{srf,p}$ = beginning time of specified time period $\Delta t_{srf,p}$ of the specified input data for the climatological conditions associated with the specification of transport conditions at the water surface in the geographic (climatological) region of the main flow channel [Eqs. (4.44)–(4.46) and (4.53), hour of the day associated with the time of calculations];

$t_{srf,p+1}$ = ending time of specified time period $\Delta t_{srf,p}$ of the specified input data for the climatological conditions associated with the specifications of transport conditions at the water surface in the geographic (climatological) region of the main flow channel [Eqs. (4.44)–(4.46) and (4.53), hour of the day associated with the time of calculations];

$t_{srm,n,p}$ = beginning time of specified time period $\Delta t_{srm,n,p}$ of the specified input data for conditions of the flow of stream or tributary n into or out of the main flow channel [Eqs. (4.68)–(4.71), hour of the day associated with the time of calculations];

$t_{srm,n,p+1}$ = ending time of specified time period $\Delta t_{srm,n,p}$ of the specified input data for conditions of the flow of stream of tributary n into or out of the main flow channel [Eqs. (4.68)–(4.71), hour of the day associated with the time of calculations];

$t_{ups,p}$ = beginning time of specified time period $\Delta t_{ups,p}$ of the specified input data for flow conditions at the upstream-end boundary enclosure surface of the main flow channel [Eqs. (4.16), (4.17), (4.20), (4.22), (4.24), (4.30), and (4.32), hour of the day associated with the time of calculations];

$t_{ups,p+1}$ = ending time of specified time period $\Delta t_{ups,p}$ of the specified input data for flow conditions at the upstream-end enclosure boundary surface of the main flow channel [Eqs. (4.16), (4.17), (4.20), (4.22), (4.24), (4.30), and (4.32), hour of the day associated with the time of calculations];

ups,N = specified input data for the number of tidal harmonics (maximum of eight) of the upstream-end tidal variation of water surface elevation at the upstream coastal open end of the main flow channel [Eq. (4.24)];

ups,n = index of the tidal harmonics of the upstream-end tidal variation of water surface elevation at the upstream coastal open end of the main flow channel [Eq. (4.24)];

$V_{wnd,avg,p}$ = specified input data for average wind speed in the geographic (climatological) region of the main flow channel, for specified time period $\Delta t_{srf,p}$ [Eq. (4.45), ft/h];

$V_{x,dis,m,p}$ = specified input data for velocity (along the curvilinear longitudinal x-axis of the main flow channel) of the discharge flow of plant m into the main flow channel, for specified time period $\Delta t_{plt,m,p}$ [Eq. (4.100), ft/h];

$\overline{V}_{x;dns}$ = specified (or calculated based on specified input data) downstream-end channel flow velocity at the downstream-end boundary enclosure surface of the main flow channel [Eqs. (4.7), (4.19), (4.29), and (4.39a), ft^3/h];

$V_{x;dns,p}$ = specified input data for downstream-end channel flow velocity at the downstream-end boundary enclosure surface of the main flow channel, for specified time period $\Delta t_{dns,p}$ [Eq. (4.19), ft/h];

$V_{x,int,m,p}$ = specified input data for velocity (along the curvilinear longitudinal x-axis of the main flow channel) of the intake flow of plant m into or out of the main flow channel, for specified time period $\Delta t_{plt,m,p}$ [Eq. (4.84), ft/h];

$V_{x,srm,n,p}$ = specified input data for velocity (along the curvilinear longitudinal x-axis of the main flow channel) of the flow of stream or tributary n into the main flow channel, for specified time period $\Delta t_{srm,n,p}$ [Eq. (4.69), ft/h];

$\bar{V}_{x,ups}$ = specified (or calculated based on specified input data) upstream-end channel flow velocity at the upstream-end boundary enclosure surface of the main flow channel [Eqs. (4.5), (4.17), (4.28), and (4.38b), ft/h];

$V_{x,ups,p}$ = specified input data for upstream-end channel flow velocity at the upstream-end boundary enclosure surface of the main flow channel, for specified time period $\Delta t_{ups,p}$ [Eq. (4.17), ft/h];

$y_{lb}(z_l)$ = specified input data for lateral location of the left bank of the bed contour of the main flow channel along the "spatially relative" lateral coordinate y of the cross section (Figs. 3.2 and 4.1) at the specified vertical location z [Eq. (4.1a), ft];

$y_{rb}(z_l)$ = specified input data for lateral location of the right bank of the bed contour of the main flow channel along the "spatially relative" lateral coordinate y of the cross section (Figs. 3.2 and 4.1) at the specified vertical location z [Eq. (4.1b), ft];

z_l = specified input data for the set of vertical locations along the "spatially relative" vertical coordinate z of the cross section (Fig. 3.2); used to specify data associated with the bed contour of the main flow channel [Eqs. (4.1a) and (4.1b), ft];

$\overline{\Delta C}_{rb,plt,m}$ = radionuclide concentration rise in plant m associated with the bottom concentration of the radionuclide in the discharge flow, representing the effect of the additional radionuclide release, into the circulating water system, on the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant m [Eqs. (4.109) and (4.110), radiologic unit/ft^3];

$\Delta C_{rb,tid;dns,p}$ = specified input data for the amplitude of the short-term periodic variation of the bottom concentration of the radionuclide in the bottom layer in the coastal region at the downstream coastal open end of the main flow channel for specified time period $\Delta t_{dns,p}$ [Eq. (4.33), radiologic unit/ft^3];

$\Delta C_{rb,tid;ups,p}$ = specified input data for the amplitude of the short-term periodic variation of the bottom concentration of the radionuclide in the bottom layer in the coastal region at the upstream coastal open end of the main flow channel, for specified time period $\Delta t_{ups,p}$ [Eq. (4.32), radiologic unit/ft^3];

$\overline{\Delta C}_{rw,plt,m}$ = radionuclide concentration rise in plant m associated with the water concentration of the radionuclide in the discharge flow, representing the effect of the additional radionuclide release, into the circulating water system, on the water concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant m [Eqs. (4.104) and (4.105), radiologic unit/ft^3];

$\Delta C_{rw,rnf,p,n}$ = specified input data for the amplitude of the nth harmonic of the difference in water concentration of the radionuclide in the rainfall, for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of the water concentration of the radionuclide in the rainfall from the specified average value of the water concentration of the radionuclide in the rainfall, during specified time period $\Delta t_{srf,p}$, in the geographic (climatological) region of the main flow channel [Eq. (4.53), radiologic unit/ft^3];

$\Delta C_{rw,tid,dns,p}$ = specified input data for the amplitude of the short-term periodic variation of the water concentration of the radionuclide in the water layer in the coastal region at the downstream coastal open end of the main flow channel, for specified time period $\Delta t_{dns,p}$ [Eq. (4.31), radiologic unit/ft^3];

$\Delta C_{rw,tid,ups,p}$ = specified input data for the amplitude of the short-term periodic variation of the water concentration of the radionuclide in the water layer in the coastal region at the upstream coastal open end of the main flow channel, for specified time period $\Delta t_{ups,p}$ [Eq. (4.30), radiologic unit/ft^3];

$\Delta g_{rnf,p,n,}$ = specified input data for the amplitude of the nth harmonic of the difference in rainfall rate (per unit area), for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of rainfall rate from the specified average rainfall rate during specified time period $\Delta t_{srf,p}$ in the geographic (climatological) region of the main flow channel [Eq. (4.44), ft/h];

$\Delta H_{grd,reg,p}$ = specified input data for the difference in water surface elevation in the groundwater table relative to the specified, temporally constant, average mean water surface elevation in the geographic (climatological) region of the main flow channel, for specified time period $\Delta t_{srf,p}$ [Eq. (4.61), ft];

$\Delta H_{mwl;dns,p}$ = specified input data for the downstream-end water surface elevation difference, for specified time period $\Delta t_{dns,p}$; used to represent the long-term variation of downstream-end mean water surface elevation (mean water level) relative to the specified constant downstream-end mean water surface elevation at the downstream coastal open end of the main flow channel [Eq. (4.25), ft];

$\Delta H_{mwl;ups,p}$ = specified input data for the upstream-end water surface elevation difference, for specified time period $\Delta t_{ups,p}$; used to represent the long-term variation of upstream-end mean water surface elevation (mean water level) relative to the specified constant upstream-end mean water surface elevation at the upstream coastal open end of the main flow channel [Eq. (4.24), ft];

$\Delta t_{dns,p}$ = a specified time period of the specified input data for flow conditions at the downstream-end boundary enclosure surface of the main flow channel [Eqs. (4.19), (4.21), (4.23), (4.25), (4.31), and (4.33), h];

$\Delta t_{grd,p}$ = a specified time period of the specified input data for groundwater seepage flow conditions in the geographic (climatological) region of the main flow channel [Eqs. (4.60), (4.61), (4.63), and (4.64), h];

Δt_{hyd} = specified constant time period for the optional specified input data for hydrodynamic conditions; used for special option applications that exclude the solution of hydrodynamic conditions in the main flow channel [Eqs. (4.113)–(4.116b), h];

$\Delta t_{plt,m,p}$ = a specified time period of the specified input data for the operational conditions of power plant m associated with the conditions of intake and discharge flows of the plant into or out of the main flow channel [Eqs. (4.19), (4.21), (4.23), (4.25), (4.31), (4.33), (4.82)–(4.86), (4.89), (4.90), (4.94)–(4.96), (4.99), (4.100), (4.103), (4.104), (4.106), (4.108), (4.109), and (4.111), h];

$\Delta t_{srf,p}$ = a specified time period of the specified input data for the climatological conditions associated with the specification of transport conditions at the water surface in the geographic (climatological) region of the main flow channel [Eqs. (4.44)–(4.46) and (4.53), h];

$\Delta t_{srm,n,p}$ = a specified time period of the specified input data for conditions of the flow of stream or tributary n into or out of the main flow channel [Eqs. (4.68)–(4.71), h];

$\Delta t_{ups,p}$ = a specified time period of the specified input data for flow conditions at the upstream-end enclosure surface of the main flow channel [Eqs. (4.16), (4.17), (4.20), (4.22), (4.24), (4.30), and (4.32), h];

$\Delta V_{wnd,p,n}$ = specified input data for the amplitude of the nth harmonic of the difference in wind speed, for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of wind speed from the specified average wind speed during specified time period $\Delta t_{srf,p}$ in the geographic (climatological) region of the main flow channel [Eq. (4.45), ft/h];

$\Delta \Theta_{wnd,ref,p,n}$ = specified input data for the amplitude of the nth harmonic of the difference in wind direction (relative to an arbitrarily specified geographic reference coordinate system), for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of wind direction from the specified average wind direction during specified time period $\Delta t_{srf,p}$ in the geographic (climatological) region of the main flow channel [Eq. (4.46), degree (or radian)];

$\eta_{int,m}$ = vertical similarity variable of the cross section of the main flow channel, based on (1) specified temporally constant depth $D_{int,m}$ of the intake of power plant m and (2) specified temporally constant depth of the bottom $D_{bot,int,m}$ of the main flow channel at the location of the intake of the power plant in the main flow channel [Eq. (4.92)];

$\Theta_{wnd,ref,avg,p}$ = specified input data for average wind direction (relative to an arbitrarily specified geographic reference coordinate system) in the geographic (climatological) region of the main flow channel for specified time period $\Delta t_{srf,p}$ [Eq. (4.46), degree (or radian)];

$\bar{\Theta}_{x,ref;i}$ = specified input data for the temporally constant angle of the direction of the curvilinear longitudinal x-axis of the main flow channel in each element i relative to an arbitrarily specified geographic coordinate system; also used to specify the direction of the wind in the geographic (climatological) region of the main flow channel [Eq. (4.47), degree];

$T_{rnf,p,n}$ = specified input data for the period of the nth harmonic of the difference in rainfall rate (per unit area) for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of rainfall rate from the specified average rainfall rate during the specified time period $\Delta t_{srf,p}$ in the geographic (climatological) region of the main flow channel [Eq. (4.44), h];

$T_{rw,rnf,p,n}$ = specified input data for the period of the nth harmonic of the difference in water concentration of the radionuclide in the rainfall, for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of the water concentration of the radionuclide in the rainfall from the specified average value of the water concentration of the radionuclide in the rainfall, during specified time period $\Delta t_{srf,p}$, in the geographic (climatological) region of the main flow channel [Eq. (4.53), h];

$T_{tid,dns,n}$ = specified input data for the period of the nth tidal harmonic of the downstream-end tidal variation of water surface elevation at the downstream coastal open end of the main flow channel [Eq. (4.25), h];

$T_{tid,ups,n}$ = specified input data for the period of the nth tidal harmonic of the upstream-end tidal variation of water surface elevation at the upstream coastal open end of the main flow channel [Eq. (4.24), h];

$T_{wnd,p,n,}$ = specified input data for the period of the nth harmonic of the difference in wind speed, for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of wind speed from the specified average wind speed, during specified time period $\Delta t_{srf,p}$ in the geographic (climatological) region of the main flow channel [Eq. (4.45), h]; and

$T_{wnd,ref,p,n}$ = specified input data for the period of the nth harmonic of the difference in wind direction (relative to an arbitrarily specified geographic reference coordinate system), for specified time period $\Delta t_{srf,p}$; used to represent the short-term variation of wind direction from the specified average wind direction, during specified time period $\Delta t_{srf,p}$, in the geographic (climatological) region of the main flow channel [Eq. (4.46), h].

4.2 FORMULATION OF SPECIFIED CROSS-SECTIONAL GEOMETRIC CONDITIONS

The formulation of the mathematical model of the RADONE computer code can incorporate detailed geometric data about the cross-sectional contours of the bed of the main flow channel by using available bathymetry information, including U.S. Coastal and Geodetic Survey Charts, which can be readily obtained for all major rivers and estuaries. The geometric input data about the cross-sectional contours can be specified with any desired degree of accuracy by (1) selecting arbitrarily specified positions along the relative vertical z-axis, with the origin corresponding to the location of maximum depth $\overline{D}_{\max}$ at any cross section of the main flow channel, and (2) specifying the distances along the lateral direction from the vertical z-axis to the left bank $y_{lb}(z_l)$ and to the right bank $y_{rb}(z_l)$ of the main flow channel (Fig. 4.1a) as

$$y_{lb}(z_l) = \text{specified at } z_l \ , \tag{4.1a}$$

$$y_{rb}(z_l) = \text{specified at } z_l \ . \tag{4.1b}$$

In certain regions of a river or an estuary that contain complex embayment areas and/or islands, the simple format of the geometric input data for specifying the locations of the left bank $y_{lb}(z_l)$ and $y_{rb}(z_l)$ [Eqs. (4.1a) and (4.1b), respectively] cannot be used directly, because the multiple cross-sectional areas in the region require special forms for specifying the multiply-connected bed contours of the main flow channel. To simplify the geometric input data, the multiple areas of an actual cross section can be combined by eliminating the multiply-connected embayment areas and/or the islands in the main flow channel and by considering a single area cross section with a simple connected bed contour profile (Fig. 4.1b), which can be readily specified according to the simple, standard format for the geometric input data [Eqs. (4.1a) and (4.1b)]. The equivalent single-area cross section can be readily constructed by the user of the RADONE computer code by considering (for the actual multiple-area cross section and the constructed single-area cross section) approximately equivalent surface widths, approximately equivalent cross-sectional areas, and approximately similar depth conditions that are consistent with the already assumed, approximately equivalent, surface width and cross-sectional area requirements.

The general computational algorithm of the RADONE computer code uses a trapezoidal integration technique to calculate all geometric properties of any cross section. This is accomplished by integrating from the bottom of the main flow channel to the level of the water surface elevation $\overline{H}$ (relative to an arbitrarily specified level) at the location of the cross section. This integration is based on specified geometric data about the locations of the left bank $y_{lb}(z_l)$ and the right bank $y_{rb}(z_l)$ at specified vertical locations z of the bed contour of the cross section of the main flow channel.

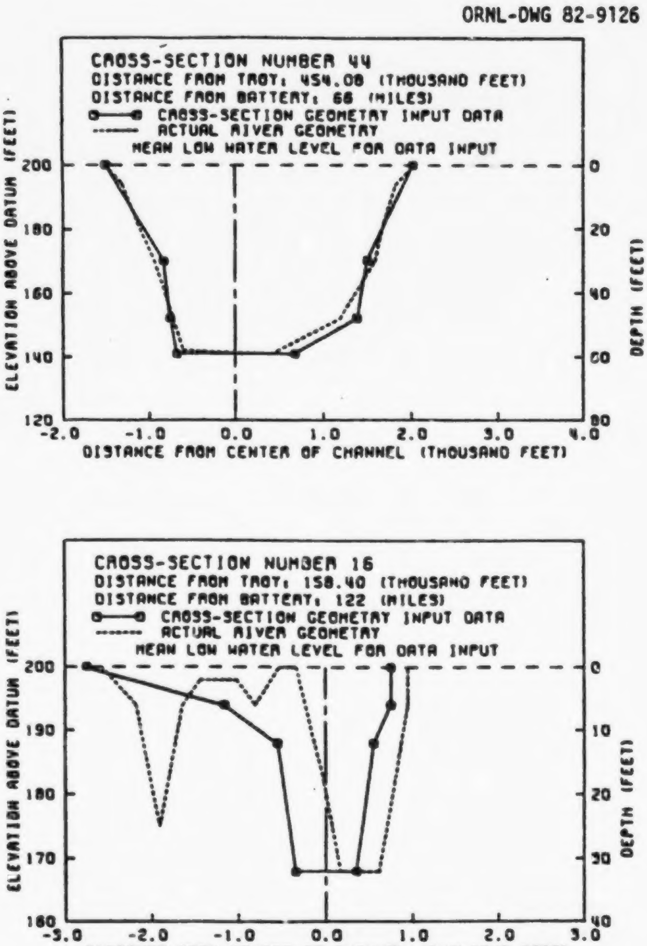

Fig. 4.1. Cross-sectional contours of the bed of the main flow channel: (*a*) simply-connected bed contour and (*b*) actual multiply-connected bed contour and modified equivalent simply-connected bed contour.

4.3 FORMULATION OF SPECIFIED END CONDITIONS

The discrete-element mathematical transport model of the RADONE computer code includes special formulations for specifying the conditions of solution variables that define the arbitrarily specified upstream- and downstream-end locations, respectively, of the curvilinear longitudinal span of the main flow channel of a river or an estuary. These variables are (1) water surface elevation $\overline{H}$, (2) channel flow rate $\overline{G}_x$ and channel flow velocity $\overline{V}_x$, (3) water concentration of the radionuclide in the water layer, and (4) bottom concentration of the radionuclide in the bottom layer at two boundary enclosure surfaces, corresponding to the upstream-end enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ of element $i = 1$ and the downstream-end enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ of element $i = N$. The general formulation of specified end conditions considers three separate cases (as user-specified options), which collectively include all possible types of flow and radionuclide transport conditions that can exist at the two specified ends of a controlled

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river and/or a tidal estuary. These three cases, considered below, are (1) simple closed-dam conditions, (2) controlled-flow dam conditions, and (3) tidal flow conditions.

4.3.1 Simple Closed-Dam Conditions

This case represents the specified end conditions associated with a simple closed dam that does not allow any inflow or outflow across the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ of the main flow channel of a river or an estuary. The water surface elevation condition at the location of the surface corresponding to the upstream-end enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or the downstream-end enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ of the main flow channel is formulated on the basis of linear extrapolation of water surface elevation in the two upstream-end internal elements $i = 1$ and $i = 2$ and/or the two downstream-end internal elements $i = N$ and $i = N - 1$, respectively, of the main flow channel. Hence, at every time step of the computations, the water surface elevation condition at the surface of the simple closed dam can be formulated directly, without requiring specified input data, based on water surface elevation in the two upstream-end internal elements, $i = 1$ and $i = 2$, and/or the two downstream-end internal elements $i = N$ and $i = N - 1$, respectively.

Upstream-end water surface elevation $\bar{H}_{i-\frac{1}{2}}$ is calculated as

$$\bar{H}_{1-\frac{1}{2}} = \bar{H}_{ups} = \bar{H}_1 + \frac{1}{(\Delta x_1 + \Delta x_2)}(\bar{H}_1 - \bar{H}_2) \ , \ \text{for all time} \ t \geqslant 0 \ . \tag{4.2}$$

Downstream-end water surface elevation $\bar{H}_{N+\frac{1}{2}}$ is calculated as

$$\bar{H}_{N+\frac{1}{2}} = \bar{H}_{dns} = \bar{H}_N + \frac{1}{(\Delta x_N + \Delta x_{N-1})}(\bar{H}_N - \bar{H}_{N-1}) \ , \ \text{for all time} \ t \geqslant 0 \ . \tag{4.3}$$

The final specified forms of (1) the upstream-end water surface elevation $\bar{H}_{i-\frac{1}{2}}$ [Eq. (4.2)] and/or (2) the downstream-end water surface elevation $\bar{H}_{N-\frac{1}{2}}$ [Eq. (4.3)] eliminate the auxiliary terms of the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)] in the upstream-end half-element $i - \frac{1}{4} = 1 - \frac{1}{4}$ and/or in the downstream-end half-element $i + \frac{1}{4} = N + \frac{1}{4}$, respectively, in terms of the values of the principal flow variables of the solution at the solution locations consisting of (a) water surface elevation $\bar{H}_1$ and $\bar{H}_2$ in the two upstream-end internal elements $i = 1$ and $i = 2$, respectively, and/or (b) water surface elevation $\bar{H}_{N-1}$ and $\bar{H}_N$ in the two downstream-end internal elements $i = N - 1$ and $i = N$, respectively. Furthermore, the final computational forms of the upstream-end water surface elevation $\bar{H}_{1-\frac{1}{2}}$ [Eq. (4.2)] and/or the downstream-end water surface elevation $\bar{H}_{N-\frac{1}{2}}$ [Eq. (4.3)] provide the required water surface elevation conditions for evaluating the detailed geometric properties of the main flow channel at the upstream-end enclosure surface at $1 - \frac{1}{2}$ in element $i = 1$ and/or at the downstream-end enclosure surface at $N + \frac{1}{2}$ in element $i = N$ (Sect. 4.2).

Channel flow rate and channel flow velocity conditions at the location of the surface of the simple closed dam, corresponding to the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ of the main flow channel, are specified as zero. This is consistent with the assumption of an impermeable surface condition that does not allow any inflow or outflow across the surface of the simple closed dam.

Upstream-end channel flow rate $\overline{G}_{x,1-\frac{1}{2}}$ is

$$\overline{G}_{x;1-\frac{1}{2}} = \overline{G}_{x;ups} = 0 \ , \ \text{for all time} \ t \geqslant 0 \ , \tag{4.4}$$

Upstream-end channel flow velocity $\overline{V}_{x;1-\frac{1}{2}}$ is

$$\overline{V}_{x;1-\frac{1}{2}} = \overline{V}_{x;ups} = 0 \ , \ \text{for all time} \ t \geqslant 0 \ . \tag{4.5}$$

Downstream-end channel flow rate $\overline{G}_{x;N+\frac{1}{2}}$ is

$$\overline{G}_{x;N+\frac{1}{2}} = \overline{G}_{x;dns} = 0 \ , \ \text{for all time} \ t \geqslant 0 \ . \tag{4.6}$$

Downstream-end channel flow velocity $\overline{V}_{x;N+\frac{1}{2}}$ is

$$\overline{V}_{x;N+\frac{1}{2}} = \overline{V}_{x;dns} = 0 \ , \ \text{for all time} \ t \geqslant 0 \ . \tag{4.7}$$

The final specified forms of (1) upstream-end channel flow rate $\overline{G}_{x;1-\frac{1}{2}}$ [Eq. (4.4)] and upstream-end channel flow velocity $\overline{V}_{x;1-\frac{1}{2}}$ [Eq. (4.5)] and/or (2) downstream-end channel flow rate $\overline{G}_{x;N+\frac{1}{2}}$ [Eq. (4.6)] and downstream-end channel flow velocity $\overline{V}_{x;N+\frac{1}{2}}$ [Eq. (4.7)] eliminate the auxiliary terms of the discrete-element system of equations, consisting of (a) the discrete-element equation for water surface elevation [Eq. (2.1)], (b) the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)], and (c) the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)] in the upstream-end half-element $i - \frac{1}{4} = 1 - \frac{1}{4}$ and in the upstream-end element $i = 1$ and/or in the downstream-end element $i = N$ and in the downstream-end half-element $i + \frac{1}{4} = N + \frac{1}{4}$, respectively.

The water concentration of the radionuclide in the water layer at the location of the surface of the simple closed dam is formulated based on the assumption of an impermeable and nonadsorbing surface for the simple closed dam, which implies zero gradient (along the curvilinear longitudinal x-axis of the main flow channel) for the water concentration of the radionuclide in the water layer at the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or at the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$.

Upstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;1-\frac{1}{2}}$ is evaluated as

$$\overline{C}_{rw;1-\frac{1}{2}} = \overline{C}_{rw;ups} = \overline{C}_{rw;1} \ , \ \text{for all time} \ t \geqslant 0 \ . \tag{4.8}$$

Downstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;N+\frac{1}{2}}$ is evaluated as

$$\overline{C}_{rw;N+\frac{1}{2}} = \overline{C}_{rw;dns} = \overline{C}_{rw;N} \ , \ \text{for all time} \ t \geqslant 0 \ . \tag{4.9}$$

The final specified forms of (1) the upstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;1-\frac{1}{2}}$ [Eq. (4.8)] and/or (2) the downstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;N+\frac{1}{2}}$ [Eq. (4.9)] eliminate the auxiliary terms of the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)] in the upstream-end element $i = 1$ and/or in the downstream-end element $i = N$, respectively, in terms of the values of the solution variable, at the solution locations, consisting of the water concentration of the radionuclide in the water layer $\overline{C}_{rw;1}$ in the upstream-end element $i = 1$ and/or the water concentration of the radionuclide in the water layer $\overline{C}_{rw,N}$ in the downstream-end element $i = N$, respectively.

Similarly, the bottom concentration of the radionuclide in the bottom layer at the location of the surface of the simple closed dam is formulated based on the same assumptions used for formulating the conditions for the water concentration of the radionuclide in the water layer [Eqs. (4.8) and (4.9)].

Upstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;1-\frac{1}{2}}$ is evaluated as

$$\overline{C}_{rb;1-\frac{1}{2}} = \overline{C}_{rb;ups} = \overline{C}_{rb;1} \;, \text{ for all time } t \geqslant 0 \;. \tag{4.10}$$

Downstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;N+\frac{1}{2}}$ is evaluated as

$$\overline{C}_{rb;N+\frac{1}{2}} = \overline{C}_{rb;dns} = \overline{C}_{rb;N} \;, \text{ for all time } t \geqslant 0 \;. \tag{4.11}$$

The final specified forms of (1) the upstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;1-\frac{1}{2}}$ [Eq. (4.10)] and/or (2) the downstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;N+\frac{1}{2}}$ [Eq. (4.11)] are used only for the computation of the maximum vertical water concentration difference $\overline{\Delta C^{\bullet}_{rw,\max}}$ (Sect. 3.4) in the water layer at the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or at the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$. Since the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)] does to include any longitudinal radionuclide transport term, the final specified forms of (1) the upstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;1-\frac{1}{2}}$ [Eq. (4.10)] and/or (2) the downstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;N+\frac{1}{2}}$ [Eq. (4.11)] are not required for eliminating any auxiliary term in the computational system.

According to the formulation of the longitudinal nonconvective transport submodel (Sect. 3.4), the upstream-end nonconvective (convection-defect) momentum transport rate $\overline{G}^{\bullet\prime}_{x;1-\frac{1}{2}}$ and/or the downstream-end nonconvective momentum transport rate $\overline{G}^{\bullet\prime}_{x;N+\frac{1}{2}}$ also becomes zero as a consequence of the assumed impermeable condition with (1) zero channel flow rate [Eq. (4.4)] and zero channel flow velocity [Eq. (4.5)] at the surface of the simple closed dam at the upstream-end enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or (2) zero channel flow rate [Eq. (4.6)] and zero channel flow velocity [Eq. (4.7)] at the surface of the simple dam at the downstream-end enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$.

Upstream-end nonconvective (convection-defect) momentum transport rate $\overline{G}^{\bullet\prime}_{x;1-\frac{1}{2}}$ is

$$\overline{G}^{\bullet\prime}_{x;i-\frac{1}{2}} = \overline{G}^{\bullet\prime}_{x;ups} = 0 \;, \text{ for all time } t \geqslant 0 \;. \tag{4.12}$$

Downstream-end nonconvective (convective-defect) momentum transport rate $\overline{G}^{\bullet\prime}_{x;N-\frac{1}{2}}$ is

$$\overline{G}^{\bullet\prime}_{x;N+\frac{1}{2}} = \overline{G}^{\bullet\prime}_{x;dns} = 0 \;, \text{ for all time } t \geqslant 0 \;. \tag{4.13}$$

The final specified forms of (1) the upstream-end nonconvective (convection-defect) momentum transport rate $\overline{G}^{\bullet\prime}_{x;1-\frac{1}{2}}$ [Eq. (4.12)] and/or (2) the downstream-end nonconvective (convection-defect) momentum transport rate $\overline{G}^{\bullet\prime}_{x;N+\frac{1}{2}}$ [Eq. (4.13)] eliminate the auxiliary terms of the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)] in the upstream-end half-element $i - \frac{1}{4} = 1 - \frac{1}{4}$ and/or in the downstream-end half-element $i + \frac{1}{4} = N + \frac{1}{4}$, respectively.

According to the formulation of the longitudinal nonconvective transport submodel (Sect. 3.4), the upstream-end nonconvective radionuclide transport rate $\overline{G}_{rw,x;1-\frac{1}{2}}$ and/or the downstream-end nonconvective radionuclide transport rate $\overline{G}_{rw,x;N+\frac{1}{2}}$ become zero as the consequences of the assumption of impermeable and nonadsorbing surface conditions at the simple closed dam at the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or at the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$.

Upstream-end nonconvective radionuclide transport rate $\overline{G}_{rw,x;1-\frac{1}{2}}$ is

$$\overline{G}_{rw,x;1-\frac{1}{2}} = \overline{G}_{rw,x;ups} = 0 \ , \ \text{for all time } t \geq 0 \ . \qquad (4.14)$$

Downstream-end nonconvective radionuclide transport rate $\overline{G}_{rw,x;N+\frac{1}{2}}$ is

$$\overline{G}_{rw,x;N+\frac{1}{2}} = \overline{G}_{rw,x;dns} = 0 \ , \ \text{for all time } t \geq 0 \ . \qquad (4.15)$$

The final specified forms of (1) the upstream-end nonconvective radionuclide transport rate $\overline{G}_{rw,x;1-\frac{1}{2}}$ [Eq. (4.14)] and/or (2) the downstream-end nonconvective radionuclide transport rate $\overline{G}_{rw,x;N+\frac{1}{2}}$ [Eq. (4.15)] eliminate the auxiliary terms of the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)] in the upstream-end element $i = 1$ and/or in the downstream-end element $i = N$, respectively.

It is not required to consider any additional conditions for the radionuclide transport conditions in the bottom layer at the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ or at the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$, since the formulation of the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)] does not include any longitudinal radionuclide transport terms.

4.3.2 Controlled-Flow Dam Conditions

This case represents the specified end conditions for controlled-flow dams with uniform or temporally varying inflow and/or outflow conditions. The formulations of controlled-flow dam conditions are based on input data, with arbitrarily specified time periods, for the solution variables, consisting of (1) channel flow rate $\overline{G}_x$ and channel flow velocity $\overline{V}_x$, (2) water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, and (3) bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$ at the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or at the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$, of the main flow channel of a river or an estuary. The formulation of the temporal variations of flow conditions is based on the general assumption that flow conditions at a controlled-flow dam can be specified as different but uniform conditions during specified time periods of possibly different durations.

The location of the surface of the controlled-flow dam corresponds to the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ of the main flow channel. The formulation of water surface elevation conditions at the surface of the controlled-flow dam is similar to the formulation of water surface elevation conditions at the simple closed dam in that it is based on the linear extrapolation of water surface elevation in the two upstream-end internal elements $i = 1$ and $i = 2$ and/or the two downstream-end internal elements $i = N$ and $i = N - 1$. Hence, at every time step of the computations, the water surface elevation condition at the surface of the controlled-flow dam can be formulated directly on the basis of water surface elevation in the two upstream-end internal elements $i = 1$ and $i = 2$ and/or the two downstream-end internal elements $i = N$ and $i = N - 1$ for all time periods and for all durations of the specified time periods of flow conditions at the controlled-flow dam; no specified input data are required. The specified forms of (1) the upstream-end water surface elevation $\overline{H}_{1-½}$ [Eq. (4.2)] and/or (2) the downstream-end water surface elevation $\overline{H}_{N+½}$ [Eq. (4.3)] again eliminate the auxiliary terms of the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)], in terms of the values of the principal flow variables of the solution at the solution locations, consisting of (a) water surface elevation $\overline{H}_1$ and $\overline{H}_2$ in the two upstream-end internal elements $i = 1$ and $i = 2$, respectively, and/or (b) water surface elevation $\overline{H}_{N-1}$ and $\overline{H}_N$ in the two downstream-end internal elements $i = N - 1$ and $i = N$, respectively. Furthermore, the final computational forms of the upstream-end water surface elevation $\overline{H}_{1-½}$ [Eq. (4.2)] and/or the downstream-end water surface elevation $\overline{H}_{N+½}$ [Eq. (4.3)] again provide the required water surface elevation conditions for evaluating the detailed geometric properties of the main flow channel at the upstream-end enclosure surface at $i - ½ = 1 - ½$ in element $i = 1$ and/or at the downstream-end enclosure surface at $i + ½ = N + ½$ in element $i = N$.

Channel flow rate and channel flow velocity conditions at the location of the surface of the controlled-flow dam, corresponding to the location of the upstream-end enclosure surface at $i - ½ = 1 - ½$ and/or the downstream-end enclosure surface at $i + ½ = N + ½$ of the main flow channel, are specified as different but uniform channel flow rate and channel flow velocity conditions during different specified time periods ($\Delta t_{ups,p}$ for the upstream-end conditions and/or $\Delta t_{dns,p}$ for the downstream-end conditions), depending on the controlled-flow conditions at the upstream and/or downstream dam, respectively.

Upstream-end channel flow $\overline{G}_{x;1-½}$ is specified as

$$\overline{G}_{x;1-½} = \overline{G}_{x;ups} = G_{x;ups,p} \ , \ \text{for time} \ \ t_{ups,p} < t \leq t_{ups,p+1} = t_{ups,p} + \Delta t_{ups,p} \ . \tag{4.16}$$

Upstream-end channel flow velocity $\overline{V}_{x;1-½}$ is specified as

$$\overline{V}_{x;1-½} = \overline{V}_{x;ups} = V_{x;ups,p} \ , \ \text{for time} \ \ t_{ups,p} < t \leq t_{ups,p+1} = t_{ups,p} + \Delta t_{ups,p} \ . \tag{4.17}$$

Downstream-end channel flow rate $\overline{G}_{x;N+½}$ is specified as

$$\overline{G}_{x;N+½} = \overline{G}_{x;dns} = G_{x;dns,p} \ , \ \text{for time} \ \ t_{dns,p} < t \leq t_{dns,p+1} + \Delta t_{dns,p} \ . \tag{4.18}$$

Downstream-end channel flow velocity $\overline{V}_{x;N+½}$ is specified as

$$\overline{V}_{x;N+½} = \overline{V}_{x;dns} = \overline{V}_{x;dns,p} \ , \ \text{for time} \ \ t_{dns,p} < t \leq t_{dns,p+1} = t_{dns,p} + \Delta t_{dns,p} \ . \tag{4.19}$$

The final specified forms of (1) the upstream-end channel flow rate $\overline{G}_{x;1-½}$ [Eqs. (4.16)] and the upstream-end channel flow velocity $\overline{V}_{x;1-½}$ [Eq. (4.17)] and/or (2) the downstream-end channel flow rate $\overline{G}_{x;N+½}$ [Eq. (4.18)] and the downstream-end channel flow velocity $\overline{V}_{x;N+½}$ [Eq. (4.19)] eliminate, according to the pseudospatial, second-upwind-differencing technique, the auxiliary terms of the discrete-element system of equations consisting of (a) the discrete-element equation for water surface elevation [Eq. (2.1)], (b) the discrete element equations for channel flow rate [Eqs. (2.2) and (2.3)], and (c) the discrete-element equation for the water concentration of the radionuclide in the water layer [Eq. (2.4)] in the upstream-end half-element $i - ¼ = 1 - ¼$ and in the upstream-end element $i = 1$ and/or in the downstream-end element $i = N$ and in the downstream-end half-element $i + ¼ = N + ¼$, respectively. The elimination of the auxiliary terms is based on the input data for specified upstream-end channel flow rate $\overline{G}_{x;ups,p}$ and channel flow velocity $\overline{V}_{x;ups,p}$ during the specified time periods $\Delta t_{ups,p}$ and/or specified downstream-end channel flow rate $\overline{G}_{x;dns,p}$ and channel flow velocity $\overline{V}_{x;dns,p}$ during the specified time periods $\Delta t_{dns,p}$.

The water concentration of the radionuclide in the water layer at the location of the surface of the controlled-flow dam is also specified as a set of different but uniform conditions for the water concentration of the radionuclide in the water layer during different specified time periods ($\Delta t_{ups,p}$ for upstream-end conditions at $i - \tfrac{1}{2} = 1 - \tfrac{1}{2}$ and/or $\Delta t_{dns,p}$ for downstream-end conditions at $i + \tfrac{1}{2} = N + \tfrac{1}{2}$), depending on controlled-flow conditions at the upstream and/or downstream dam, respectively.

Upstream-end water concentration of the radionuclide in the water layer $\bar{C}_{rw;1-1/2}$ is specified as

$$\bar{C}_{rw;1-1/2} = \bar{C}_{rw;ups} = C_{rw;ups,p}\ , \quad \text{for time} \quad t_{ups,p} < t \leqslant t_{ups,p+1} = t_{ups,p} + \Delta t_{ups,p}\ . \qquad (4.20)$$

Downstream-end water concentration of the radionuclide in the water layer $\bar{C}_{rw;N+1/2}$ is specified as

$$\bar{C}_{rw;N+1/2} = \bar{C}_{rw;dns} = C_{rw;dns,p}\ , \quad \text{for time} \quad t_{dns,p} < t \leqslant t_{dns,p+1} = t_{dns,p} + \Delta t_{dns,p}\ . \qquad (4.21)$$

The final specified forms of (1) the upstream-end water concentration of the radionuclide in the water layer $\bar{C}_{rw;1-1/2}$ [Eq. (4.20)] and/or (2) the water concentration of the radionuclide in the water layer $\bar{C}_{rw;N+1/2}$ [Eq. (4.21)] eliminate, according to the pseudospatial, second-upwind-differencing technique the auxiliary terms of the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)] in the upstream element $i = 1$ and/or in the downstream-end element $i = N$, respectively. The elimination of the auxiliary terms is based on the input data for specified upstream-end water concentration of the radionuclide in the water layer $C_{rw;ups,p}$ during the specified time periods $\Delta t_{ups,p}$ and/or on the input data for specified downstream-end water concentration during the specified time periods $\Delta t_{dns,p}$.

Similarly, the bottom concentration of the radionuclide in the bottom layer at the location of the surface of the controlled-flow dam is also specified as a set of different but uniform conditions for the bottom concentration of the radionuclide in the bottom layer during different specified time periods ($\Delta t_{ups,p}$ for upstream-end conditions and/or $\Delta t_{dns,p}$ for downstream-end conditions), depending on controlled-flow conditions at the upstream and/or downstream dam, respectively.

Upstream-end bottom concentration of the radionuclide in the bottom layer $\bar{C}_{rb;1-1/2}$ is specified as

$$\bar{C}_{rb;1-1/2} = \bar{C}_{rb;ups} = C_{rb;ups,p}\ , \quad \text{for time} \quad t_{ups,p} < t \leqslant t_{ups,p+1} = t_{ups,p} + \Delta t_{ups,p}\ . \qquad (4.22)$$

Downstream-end bottom concentration of the radionuclide in the bottom layer $\bar{C}_{rb;N+1/2}$ is specified as

$$\bar{C}_{rb;N+1/2} = \bar{C}_{rb;dns} = C_{rb;dns,p}\ , \quad \text{for time} \quad t_{dns,p} < t \leqslant t_{dns,p+1} = t_{dns,p} + \Delta t_{dns,p}\ . \qquad (4.23)$$

Again, the final specified forms of (1) the upstream-end bottom concentration of the radionuclide in the bottom layer $\bar{C}_{rb;1-1/2}$ [Eq. (4.22)] and/or (2) the downstream-end bottom concentration of the radionuclide in the bottom layer $\bar{C}_{rb;N+1/2}$ [Eq. (4.23)] are used only for the computation of the maximum vertical water concentration difference $\overline{\Delta C}^{*}_{rw,\max}$ (Sect. 3.4) in the water layer at the upstream-end boundary enclosure surface at $i - \tfrac{1}{2} = 1 - \tfrac{1}{2}$ and/or at the downstream-end boundary enclosure surface at $i + \tfrac{1}{2} = N + \tfrac{1}{2}$. Since the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)] does not include any longitudinal radionuclide transport term, the final specified forms of (1) the upstream-end bottom concentration of the radionuclide in the bottom layer $\bar{C}_{rb;1-1/2}$ [Eq. (4.22)] and/or (2) the downstream-end bottom concentration of the radionuclide in the bottom layer $\bar{C}_{rb;N+1/2}$ [Eq. (4.23)] are not required for eliminating any auxiliary term in the computational system.

The computational algorithm of the RADONE computer code automatically invokes the general second-upwind-differencing technique (Sect. 3.3.2) for determining the computational values of upstream- and/or downstream-end conditions of all transportive intrinsic solution variables associated with convective transport in the water layer at the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or at the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ of the main flow channel. The determination of the computational values of the intrinsic flow variables is based on the specified values of upstream-end channel flow rate $\overline{G}_{x;1-\frac{1}{2}}$ [Eq. (4.16)] during the specified time periods $\Delta t_{ups,p}$ and/or downstream-end channel flow rate $\overline{G}_{x;N+\frac{1}{2}}$ [Eq. (4.20)] during the time periods $\Delta t_{dns,p}$ (Sect. 4.3.4).

Considering flow conditions at the surface of a controlled-flow dam, nonconvective transport rates are definitely negligible in comparison with the convective transport rates of transportive intrinsic flow variables in the water layer under specified conditions of channel flow rate at the upstream-end enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or at the downstream-end enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ of the main flow channel of a river or an estuary.

Therefore, the formulation of end conditions for a controlled-flow dam is similar to the formulation of specified end conditions for a simple closed dam in that is also considers zero nonconvective transport rates at the upstream-end enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or at the downstream-end enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ for:

1. upstream-end nonconvective (convection-defect) momentum transport rate $\overline{G}^{*\prime}_{x,1-\frac{1}{2}}$ [Eq. (4.12)] and/or downstream-end nonconvective momentum transport rate $\overline{G}^{*\prime}_{x;N+\frac{1}{2}}$ [Eq. (4.13)],
2. upstream-end nonconvective radionuclide transport rate $\overline{G}_{rw,x;1-\frac{1}{2}}$ [Eq. (4.14)] and/or downstream-end nonconvective radionuclide transport rate $\overline{G}_{rw,x;N+\frac{1}{2}}$ [Eq. (4.15)].

Hence, for controlled-flow dam conditions, the final specified forms of (1) the upstream-end nonconvective (convection-defect) momentum transport rate $\overline{G}^{*\prime}_{x,1-\frac{1}{2}}$ [Eq. (4.12)] and/or (2) downstream-end nonconvective (convection-defect) momentum transport rate $\overline{G}^{*\prime}_{x;1+\frac{1}{2}}$ [Eq. (4.13)] eliminate the auxiliary terms of the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)] in the upstream-end half-element $i - \frac{1}{4} = 1 - \frac{1}{4}$ and/or in the downstream-end half-element $i + \frac{1}{4} = N + \frac{1}{4}$, respectively.

Similarly, for controlled-flow dam conditions, the final specified forms of (1) the upstream-end radionuclide transport rate $\overline{G}_{rw,x;1-\frac{1}{2}}$ [Eq. (4.14)] and/or (2) the downstream-end radionuclide transport rate $\overline{G}_{rw,x;N+\frac{1}{2}}$ [Eq. (4.15)] eliminate the auxiliary terms of the discrete-element equation for water-concentration of the radionuclide in the water layer [Eq. (2.16)] in the upstream-end element $i = 1$ and/or the downstream-end element $i = N$, respectively.

4.3.3 Tidal Flow Conditions

This case represents open-end boundary conditions at the upstream and/or downstream end of the main flow channel of an estuary when the boundary of the enclosure surface is open to a coastal region where flow conditions are controlled by geostrophic currents and multiharmonic tidal conditions.

The water surface elevation condition at the location of the enclosure surface, corresponding to the upstream-end enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or the downstream-end enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ of the main flow channel, is formulated by considering the sum of the three parts of water surface elevation conditions that usually exist at the tidal-dominated ocean end:

1. The constant mean water surface elevation (mean water level), which represents the long-term, constant average value of water surface elevation at the coastal open end of the estuary, is specified as input data.
2. The long-term variation of mean water surface elevation (mean water level) relative to the constant mean water surface elevation is specified as a set of input data for the different values of water surface elevation, which remain uniform during specified time periods of possibly different durations.
3. The short- and long-term multiharmonic tidal variations of water surface elevation are specified as a set of input data for each tidal harmonic (maximum of eight harmonics), consisting of amplitude, period, and lag time (relative to midnight) of the tidal harmonic, based on available information about tidal conditions in the coastal region [e.g., Hendershott and Munk (1970), Schureman (1958)].

Upstream-end water surface elevation $\bar{H}_{1-½}$ is calculated as

$$\bar{H}_{1-½} = \bar{H}_{ups} = \bar{H}_{mwl;ups} + \Delta H_{mwl;ups,p}$$

$$+ \sum_{ups,n=1}^{ups,N} H_{tid;ups,n} \cos\left[\frac{2\pi}{T_{tid;ups,n}}(t - t_{lag;ups,n})\right] ,$$

$$\text{for time} \quad t_{ups,p} < t \leqslant t_{ups,p+1} = t_{ups,p} + \Delta t_{ups,} \ . \tag{4.24}$$

Downstream-end water surface elevation $\bar{H}_{N+½}$ is calculated as

$$\bar{H}_{N+½} = \bar{H}_{dns} = \bar{H}_{mwl;dns} + \Delta H_{mwl;dns,p}$$

$$+ \sum_{dns,n=1}^{dns,N} H_{tid;dns,n} \cos\left[\frac{2\pi}{T_{tid;dns,n}}(t - t_{lag;dns,n})\right] ,$$

$$\text{for time} \quad t_{dns,p} < t \leqslant t_{dns,p+1} = t_{dns,p} + \Delta t_{dns,p} \ . \tag{4.25}$$

Amplitudes, periods, and lag times of tidal harmonics are specified as independent of the durations of the specified time periods ($\Delta t_{ups,p}$ for upstream-end conditions and $\Delta t_{dns,p}$ for downstream-end conditions) in Eqs. (4.24) and (4.25), because an eight-term formulation of tidal surface elevation can simulate, for long periods (more than a year), most of the important long-period, diurnal and semidiurnal constituents of the tide spectra in any coastal region [e.g., Hendershott and Munk (1970), Schureman (1958)].

The final forms of (1) the upstream-end water surface elevation $\bar{H}_{1-½}$ [Eq. (4.24)] and/or (2) the downstream-end water surface elevation $\bar{H}_{N+½}$ [Eq. (4.25)] eliminate the auxiliary terms of the discrete-element equations for the channel flow rate [Eqs. (2.2) and (2.3)] in the upstream-end half-element $i - ¼ = 1 - ¼$ and/or in the downstream-end half-element $i + ¼ = 1 + ¼$, respectively, in terms of specified input data about tidal surface elevation conditions at (1) the upstream coastal open end at $i - ½ = 1 - ½$ and/or (2) the downstream coastal open end at $i + ½ = N + ½$, respectively, of the estuary. Furthermore, the final computational forms of (1) the upstream-end water surface elevation $\bar{H}_{1-½}$ [Eq. (4.24)] and/or (2) the downstream-end water surface elevation $\bar{H}_{N+½}$ [Eq. (4.25)] provide the required water surface elevation conditions for evaluating the detailed geometric properties of the main flow channel at the upstream-end enclosure surface at $1 - ½$ in element $i = 1$ and/or at the downstream-end enclosure surface at $N + ½$ in element $i = N$.

In general, channel flow rate $\overline{G}_x$ and the longitudinally transportive intrinsic flow variables, channel flow velocity $\overline{V}_x$, and water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, as well as the longitudinally nontransportive bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$, at a coastal open end of an estuary cannot be specified accurately during the inflowing flood stage of the tidal conditions. Hence, the specifications of the coastal open-end conditions can be based only on formal considerations of flow conditions that generally exist in the main flow channel of the estuary and also in the coastal region that includes the coastal open end of the estuary [e.g., Eraslan (1974, 1975), Thatcher and Harleman (1972), Leendertse and Liu (1975)].

Channel flow rate $\overline{G}_x$ at the location of the surface of the coastal open end, corresponding to the upstream-end enclosure surface at $i - \tfrac{1}{2} = 1 - \tfrac{1}{2}$ and/or the downstream-end enclosure surface at $i + \tfrac{1}{2} = N + \tfrac{1}{2}$ of the main flow channel, is formally specified based on the linear extrapolation of channel flow rate in the two upstream-end internal half-elements $i - \tfrac{1}{4} = 1 - \tfrac{1}{4}$ and $i + \tfrac{1}{4} = 1 + \tfrac{1}{4}$ and/or in the two downstream-end internal half-elements $i - \tfrac{1}{4} = N - \tfrac{1}{4}$ and $i + \tfrac{1}{4} = N + \tfrac{1}{4}$, respectively, of the main flow channel. Hence, at every time step of the computations, channel flow rate at the location of the surface of the coastal open end can be formulated directly, based on channel flow rate in the two upstream-end internal half-elements and/or the two downstream-end internal half-elements; no specified input data are required.

Upstream-end channel flow rate $\overline{G}_{x;1-\frac{1}{4}}$ is calculated as

$$\overline{G}_{x;1-\frac{1}{2}} = \overline{G}_{x;ups} = \overline{G}_{x;1-\frac{1}{4}} + \frac{1}{2}(\overline{G}_{x;1-\frac{1}{4}} - \overline{G}_{x;1+\frac{1}{4}}) \text{ , for all time } t \geqslant 0 \text{ .} \tag{4.26}$$

Downstream-end channel flow rate $\overline{G}_{x;N+\frac{1}{2}}$ is calculated as

$$\overline{G}_{x;N+\frac{1}{2}} = \overline{G}_{x;dns} = \overline{G}_{x;N+\frac{1}{4}} + \frac{1}{2}(\overline{G}_{x;N+\frac{1}{4}} - \overline{G}_{x;N-\frac{1}{4}}) \text{ , for all time } t \geqslant 0 \text{ .} \tag{4.27}$$

Channel flow velocity $\overline{V}_x$ at the location of the surface of the coastal open end is formally specified based on the general definition of cross-section-averaged channel flow velocity, which is in terms of (1) the channel flow rate and (2) the cross-sectional area representing the mean area of the cross section of the channel segment.

Upstream-end channel flow velocity $\overline{V}_{x;ups}$ is calculated as

$$\overline{V}_{x;ups} = \frac{\overline{G}_{x;ups}}{\overline{A}_{1-\frac{1}{2}}} = \frac{\overline{G}_{x;1-\frac{1}{2}}}{\overline{A}_{1-\frac{1}{2}}} \text{ , for all time } t \geqslant 0 \text{ .} \tag{4.28}$$

Downstream-end channel flow velocity $\overline{V}_{x;dns}$ is calculated as

$$\overline{V}_{x;dns} = \frac{\overline{G}_{x;dns}}{\overline{A}_{N+\frac{1}{2}}} = \frac{\overline{G}_{x;N+\frac{1}{2}}}{\overline{A}_{N+\frac{1}{2}}} \text{ , for all time } t \geqslant 0 \text{ .} \tag{4.29}$$

The final interpolated forms of (1) the upstream-end channel flow rate $\overline{G}_{x;1-\frac{1}{2}}$ [Eq. (4.26)] and the upstream-end channel flow velocity $\overline{V}_{x;ups}$ [Eq. (4.28)] and/or (2) the downstream-end channel flow rate $\overline{G}_{x;N+\frac{1}{2}}$ [Eq. (4.27)] and the downstream-end channel flow velocity $\overline{V}_{x;dns}$ [Eq. (4.29)] eliminate, according to the pseudospatial, second-upwind-differencing technique, the auxiliary terms of the discrete-element system of equations, consisting of (a) the discrete-element equation for water surface elevation [Eq. (2.1)], (b) the discrete-element equations for the channel flow rate [Eqs. (2.2) and (2.3)], and (c) the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)], in the upstream-end half-element $i - \frac{1}{4} = 1 - \frac{1}{4}$ and in the upstream-end element $i = 1$, and/or in the downstream-end element $i = N$ and in the downstream-end half-element $i + \frac{1}{4} = N + \frac{1}{4}$, respectively. The elimination of the auxiliary terms is based on the values of the solution variables at the solution locations, consisting of (1) the channel flow rates $\overline{G}_{x;1-\frac{1}{4}}$ and $\overline{G}_{x;1+\frac{1}{4}}$ in the two upstream-end internal half-elements $i - \frac{1}{4} = 1 - \frac{1}{4}$ and $i + \frac{1}{4} = 1 + \frac{1}{4}$, and/or (2) the channel flow rates $\overline{G}_{x;N-\frac{1}{4}}$ and $\overline{G}_{x;N+\frac{1}{4}}$ in the two downstream-end internal half-elements $i - \frac{1}{4} = N - \frac{1}{4}$ and $i + \frac{1}{4} = N + \frac{1}{4}$, respectively.

The specification of the radionuclide concentration conditions at the coastal open end boundary enclosure surface of the main flow channel requires careful consideration of all possible radionuclide concentration conditions that can exist in the coastal region external to the main flow channel of the estuary. It should be emphasized that the radionuclide concentration conditions at the coastal open end boundary enclosure surface of the main flow channel of an estuary cannot be specified accurately during the inflowing flood stage of the tidal conditions, unless reasonably accurate information is available as temporally varying concentration conditions in the vicinity of the coastal open end enclosure boundary surface, based on the available information about the temporally and spatially varying radionuclide concentration conditions in the coastal region. Furthermore, it is important to point out that the level of accuracy required in the specification of the radionuclide concentration conditions at the coastal open end boundary enclosure surface for simulating the radionuclide concentration conditions, along the curvilinear longitudinal x-axis of the main flow channel of the estuary, depends on the particular radionuclide release scenario, which usually belongs to one of the two general classes of radionuclide release scenarios.

The first class of interior radionuclide release scenarios includes all radionuclide release scenarios that can occur within the assumed computational region of the main flow channel of the estuary. For this class of interior radionuclide release scenarios, the coastal region, exterior to the coastal open end boundary enclosure surface of the main flow channel, generally behaves as a large uncontaminated body of water that periodically supplies water, with relatively very low levels of radionuclide concentrations, into the main flow channel of the estuary, at the coastal open end boundary enclosure surface, during the inflowing flood stages of the tidal conditions. Therefore, since the local radionuclide concentration conditions, along the curvilinear longitudinal x-axis of the main flow channel of the estuary, will always be significantly higher than the radionuclide concentration conditions in the coastal region, external to the main flow channel, it is generally not essential that the radionuclide concentration conditions be specified accurately at the coastal open end boundary enclosure surface of the main flow channel, during the inflowing flood stages of the tidal conditions.

The second class of exterior radionuclide release scenarios includes all radionuclide release scenarios that can occur in the coastal region, exterior to the assumed computational region of the main flow channel of the estuary, but in the vicinity of the coastal open end boundary enclosure surface of the main flow channel. For this class of exterior radionuclide release scenarios, the coastal region, exterior to the coastal open end boundary enclosure surface of the main flow channel, generally behaves as a large contaminated body of water that periodically supplies water, with relatively very high levels of radionuclide concentrations, into the main flow channel of the estuary, at the coastal open end boundary enclosure surface, during the inflowing flood stages of the tidal conditions. Therefore, conversely, since the radionuclide concentration conditions in the coastal region, external to the main flow channel, will generally be higher than the local radionuclide concentration conditions, along the curvilinear longitudinal x-axis of the main flow channel, it is essential that the radionuclide concentration conditions be specified accurately, including accurate and detailed temporal variations of the radionuclide concentration conditions, at the coastal open end boundary enclosure surface of the main flow channel, during the inflowing flood stages of the tidal conditions. Hence, for the second class of exterior radionuclide release scenarios, any attempt to simulate the local radionuclide concentration conditions, along the longitudinal curvilinear x-axis of the main flow channel, will be unsuccessful, unless reliable, accurate, and reasonably detailed information is available about the temporal variations of the radionuclide concentration conditions at the coastal open end boundary enclosure surface of the main flow channel of the estuary.

The general mathematical formulation of the RADONE computer code includes all the necessary capabilities for accurate specification of the coastal open end conditions for water concentration of the radionuclide in the water layer based on reasonably detailed site-specific information about the conditions for water concentration of the radionuclide in the water layer in the coastal region. This site-specific information can include:

1. the long-term variations of water concentrations of the radionuclide in the water layer (excluding harmonic variations) in the coastal region in the form of specified different but uniform values for water concentration of the radionuclide in the water layer during the different specified time periods ($\Delta t_{ups,p}$ for the upstream-end conditions and/or $\Delta t_{dns,p}$ for the downstream-end conditions) and
2. the short-term periodic variations of water concentration of the radionuclide in the water layer in the coastal region that can be approximated on the basis of the first dominant tidal harmonic term (generally the short-period term) of the tidal variation of water surface elevation conditions in the coastal region, with specified different but uniform values for the amplitudes of the periodic variations of water concentration of the radionuclide in the water layer during the different specified time periods ($\Delta t_{ups,p}$ for the upstream-end conditions and/or $\Delta t_{dns,p}$ for the downstream-end conditions).

Hence, the input data to the RADONE computer code for specifying coastal open end boundary conditions for the water concentration of the radionuclide in the water layer at the location of the coastal open end, corresponding to the upstream-end enclosure boundary surface at $i - ½ = 1 - ½$ and/or to the downstream-end boundary enclosure surface at $i + ½ = N + ½$ of the main flow channel, can include detailed site-specific information about the tidal variations of the water concentration of the radionuclide in the water layer in the coastal region.

Upstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;1-½}$ can be formulated as

$$\overline{C}_{rw;1-½} = \overline{C}_{rw;ups} = C_{rw,avg;ups,p} + \Delta C_{rw,tid;ups,p} \times \cos\left[\frac{2\pi}{\mathrm{T}_{tid;ups,1}}(t - t_{lag;ups,1})\right] ,$$

$$\text{for time } t_{ups,p} < t \leqslant t_{ups,p+1} = t_{ups,p} + \Delta t_{ups,p} . \qquad (4.30)$$

Downstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;N+½}$ can be formulated as

$$\overline{C}_{rw;N+½} = \overline{C}_{rw;dns} = C_{rw,avg;dns,p}$$

$$+ \Delta C_{rw,tid;dns,p} \times \cos\left[\frac{2\pi}{T_{tid;dns,1}}(t - t_{lag;dns,1})\right] ,$$

$$\text{for time } t_{dns,p} < t \leqslant t_{dns,p+1} = t_{dns,p} + \Delta t_{dns,p} \ . \qquad (4.31)$$

The final specified tidal forms of (1) the upstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;1-½}$ [Eq. (4.30)] and/or (2) the downstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;N+½}$ [Eq. (4.31)] eliminate, according to the pseudospatial second-upwind-differencing technique, the auxiliary terms of the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)] in the upstream-end element $i = 1$ and/or in the downstream-end element $i = N$ based on the input data for the specified conditions for water concentration of the radionuclide in the water layer at the coastal open end of the main flow channel of the estuary.

Similarly, the general mathematical formulation of the RADONE computer code includes all the necessary capabilities for accurate specification of the coastal open end conditions for bottom concentration of the radionuclide in the bottom layer based on reasonably detailed site-specific information about the conditions for bottom concentration of the radionuclide in the bottom layer in the coastal region. This site-specific information can include the following:

1. long-term variations of bottom concentration of the radionuclide in the bottom layer (excluding harmonic variations) in the coastal region in the form of specified different but uniform values for bottom concentration of the radionuclide in the bottom layer during the different specified time periods ($\Delta t_{ups,p}$ for the upstream-end conditions and/or $\Delta t_{dns,p}$ for the downstream-end conditions) and
2. the short-term periodic variations of bottom concentration of the radionuclide in the bottom layer in the coastal region that can be approximated on the basis of the first dominant tidal harmonic term (generally the short-period term) of the tidal variation of water surface elevation conditions in the coastal region, with specified different but uniform values for the amplitudes of the periodic variations of bottom concentration of the radionuclide in the bottom layer during the different specified time periods ($\Delta t_{ups,p}$ for the upstream-end conditions and/or $\Delta t_{dns,p}$ for the downstream-end conditions).

Hence, similarly, the input data to the RADONE computer code for specifying coastal open end boundary conditions for bottom concentration of the radionuclide in the bottom layer a the location of the coastal open end, corresponding to the upstream-end enclosure boundary surface at $i - ½ = 1 - ½$ and/or to the downstream-end enclosure boundary surface at $i + ½ = N + ½$ of the main flow channel, can include detailed site-specific information about the tidal variations of the bottom concentration of the radionuclide in the bottom layer in the coastal region.

Upstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;1-½}$ can be formulated as

$$\overline{C}_{rb;1-½} = \overline{C}_{rb;ups} = C_{rb,avg;ups,p}$$

$$+ \Delta C_{rb,tid;ups,p} \times \cos\left[\frac{2\pi}{T_{tid;ups,1}}(t - t_{lag;ups,1})\right]$$

$$\text{for time } t_{ups,p} < t \leq t_{ups,p+1} = t_{ups,p} + \Delta t_{ups,p} \ . \tag{4.32}$$

Downstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;N+½}$ can be formulated as

$$\overline{C}_{rb;N+½} = \overline{C}_{rb;dns} = C_{rb,avg;dns,p}$$

$$+ \Delta C_{rb,tid;dns,p} \times \cos\left[\frac{2\pi}{\mathrm{T}_{tid;dns,1}}(t - t_{lag;dns,1})\right] ,$$

$$\text{for time } t_{dns,p} < t \leq t_{dns,p+1} = t_{dns,p} + \Delta t_{dns,p} \ . \tag{4.33}$$

Again, the final specified tidal forms of (1) the upstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;1-½}$ [Eq. (4.32)] and/or (2) the downstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;N+½}$ [Eq. (4.33)] are used only for the computation of the maximum vertical water concentration difference $\overline{\Delta C^{*}_{rw,\max}}$ (Sect. 3.4) in the water layer at the upstream-end boundary enclosure surface at $i - ½ = 1 - ½$ and/or at the downstream-end boundary enclosure surface at $i + ½ = N + ½$. Since the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)] does not include any longitudinal radionuclide transport term, the final specified forms of (1) the upstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;1-½}$ [Eq. (4.32)] and/or (2) the downstream-end concentration of the radionuclide in the bottom layer $\overline{C}_{rb;N+½}$ [Eq. (4.33)] are not required for eliminating any auxiliary term in the computational system.

The computational algorithm of the RADONE computer code automatically invokes the general second-upwind-differencing technique (Sect. 3.3.2) for determining the computational values of the upstream- and/or downstream-end coastal open end conditions of all transportive intrinsic solution variables associated with the convective transport in the water layer at the upstream-end coastal boundary enclosure surface at $i - ½ = 1 - ½$ and/or at the downstream-end coastal boundary enclosure surface at $i + ½ = N + ½$ of the main flow channel.

Furthermore, the mathematical formulation of the RADONE computer code evaluates all nonconvective transport rates (along the curvilinear longitudinal x-axis of the main flow channel, consisting of (1) nonconvective (convection-defect) momentum transport rates $\overline{G}_x^{*\prime}$ (Sect. 3.4.4) and (2) nonconvective radionuclide transport rates $\overline{G}_{rw,x}$ (Sect. 3.4.5), at the upstream-end coastal boundary enclosure surface at $i - ½ = 1 - ½$ and/or at the downstream-end coastal boundary enclosure surface at $i + ½ = N + ½$ of the main flow channel, based on the standard formulations of the longitudinal nonconvective transport submodel (Sect. 3.4). Hence, for specified tidal flow conditions associated with coastal open end boundary enclosure surfaces, the general mathematical formulation of the RADONE computer code does not require any additional specified boundary condition for evaluating the longitudinal nonconvective transport rates at the upstream-end coastal boundary enclosure surface at $i - ½ = 1 - ½$ and/or at the downstream-end coastal boundary enclosure surface at $i + ½ = N + ½$ of the main flow channel of the estuary.

4.3.4 Approximate Formulation of Unknown End Conditions

The mathematical model of the RADONE computer code also includes two user-specified alternative options for formulating, based on a minimal amount of available information, the approximate conditions for the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ and for the bottom concentration of the radionuclide in the bottom layer for controlled-flow dam conditions or for coastal open end conditions that correspond to the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ of the main flow channel. These user-specified alternative options are included particularly in the applications of the RADONE computer code to the simulations of the radionuclide concentration conditions in a river or an estuary which result from the first class of interior radionuclide release scenarios, which includes all radionuclide release scenarios that can occur within the assumed computational region of the main flow channel. These options enable the user to implement the RADONE computer code in simulating the distributions (along the curvilinear longitudinal x-axis of the main flow channel) of the local conditions for the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ and the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$ of an actual controlled river or a tidal estuary by utilizing any amount and form of available site-specific information about the radionuclide concentration conditions at the controlled-flow dam and/or in the coastal region that includes the coastal open end of the estuary. Hence, the level of accuracy and the amount of available site-specific information about the radionuclide concentration conditions at the upstream-end boundary enclosure surface and/or at the downstream-end boundary enclosure surface of the main flow channel do not impose any limitation on the applicability of the RADONE computer code to the simulation of approximate but physically realistic distributions (along the curvilinear longitudinal x-axis of the main flow channel) of radionuclide concentration conditions in an actual controlled river or a tidal estuary.

The first alternative option for specifying controlled-flow dam conditions or coastal open end conditions for the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ requires a minimal amount of available information about the general conditions of water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ in the vicinities of the boundary enclosure surfaces. Based on the limited amount of available information about the variations of the conditions for water concentration of the radionuclide in the water layer at the upstream end and/or at the downstream end of the main flow channel, the formulation of the conditions for the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ at the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or at the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ considers two specified constant limiting values for the water concentration of the radionuclide in the water layer as specified constant minimum allowable values and as specified constant maximum allowable values. The formulation of the water concentration of the radionuclide in the water layer at the location of the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or at the location of the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ is based on the approximate but plausible assumption that the water concentration of the radionuclide in the water layer generally remains about the same as the water concentration of the radionuclide in the water layer in the upstream-end element $i = 1$ and/or in the downstream-end element $i = N$, respectively, provided that the value of the water concentration of the radionuclide in the water layer remains within the specified constant limiting value of water concentration of the radionuclide for the specified controlled-flow dam conditions or for the specified coastal open end conditions.

Upstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;1-\frac{1}{2}}$ is formulated as

$$\overline{C}_{rw;1-\frac{1}{2}} = \overline{C}_{rw;ups} \quad ; \qquad (4.34a)$$

$$\text{if } \overline{C}_{rw;ups} < C_{rw,\min;ups} \; : \; \overline{C}_{rw;ups} = C_{rw,\min;ups} \;, \text{ for all time } t \geqslant 0 \; ; \qquad (4.34b)$$

$$\text{if } \overline{C}_{rw;ups} > C_{rw,\max;ups} \ : \ \overline{C}_{rw,ups} = C_{rw,\max;ups} \ , \ \text{for all time } t \geqslant 0 \ . \qquad (4.34c)$$

Downstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;N+\frac{1}{2}}$ is formulated as

$$\overline{C}_{rw;N+\frac{1}{2}} = \overline{C}_{rw;dns} \ ; \qquad (4.35a)$$

$$\text{if } \overline{C}_{rw;dns} < C_{rw,\min;dns} \ : \ \overline{C}_{rw;dns} = C_{rw,\min;dns} \ , \ \text{for all time } t \geqslant 0 \ ; \qquad (4.35b)$$

$$\text{if } \overline{C}_{rw;dns} > C_{rw,\max;dns} \ : \ \overline{C}_{rw;dns} = C_{rw,\max;dns} \ , \ \text{for all time } t \geqslant 0 \ . \qquad (4.35c)$$

The final approximate forms of (1) the upstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;1-\frac{1}{2}}$ [Eqs. (4.34a), (4.34b), and (4.34c)] and/or (2) the downstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;N+\frac{1}{2}}$ [Eqs. (4.35a), (4.35b), and (4.35c)] eliminate, according to the generalized, pseudospatial second-upwind-differencing technique, the auxiliary terms of the discrete-element equations for water concentration of the radionuclide in the water layer [Eq. (2.4)] in the upstream-end element $i = 1$ and/or in the downstream-end element $i = N$, based on the input data for approximate limiting conditions for water concentration of the radionuclide in the water layer.

Similarly, the second alternative option for specifying controlled-flow dam conditions or coastal open end conditions for the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$ requires a minimal amount of available information about the general conditions of the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$ in the vicinities of the boundary enclosure surfaces. Based on the limited amount of available information about the variations of the conditions for bottom concentration of the radionuclide in the bottom layer at the upstream end and/or at the downstream end of the main flow channel, the formulation of the conditions for the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$ at the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or at the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ also considers two specified constant limiting values for the bottom concentration of the radionuclide in the bottom layer as specified constant minimum allowable values and as specified constant maximum allowable values. The formulation of the bottom concentration of the radionuclide in the bottom layer at the location of the upstream-end boundary enclosure surface at $i - \frac{1}{2} = 1 - \frac{1}{2}$ and/or at the location of the downstream-end boundary enclosure surface at $i + \frac{1}{2} = N + \frac{1}{2}$ is also based on the approximate but plausible assumption that the bottom concentration of the radionuclide in the bottom layer generally remains about the same as the bottom concentration of the radionuclide in the bottom layer in the upstream-end element $i = 1$ and/or in the downstream-end element $i = N$, respectively, provided that the value of the bottom concentration of the radionuclide in the bottom layer remains within the specified constant limiting values of the bottom concentration of the radionuclide for the specified controlled-flow dam conditions or for the specified coastal open-end conditions.

Upstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;1-\frac{1}{2}}$ is formulated as

$$\overline{C}_{rb;1-\frac{1}{2}} = \overline{C}_{rb;ups} \ ; \qquad (4.36a)$$

$$\text{if } \overline{C}_{rb;ups} < C_{rb,\min;ups} \ : \ \overline{C}_{rb;ups} = C_{rb,\min;ups} \ , \ \text{for all time } t \geqslant 0 \ ; \qquad (4.36b)$$

$$\text{if } \overline{C}_{rb;ups} > C_{rb,\max;ups} \ : \ \overline{C}_{rb;ups} = C_{rb,\max;ups} \ , \text{ for all time } t \geqslant 0 \ . \tag{4.36c}$$

Downstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;N+½}$ is formulated as

$$\overline{C}_{rb;N+½} = \overline{C}_{rb;dns} \ ; \qquad ([illegible]a)$$

$$\text{if } \overline{C}_{rb;dns} < C_{rb,\min;dns} \ : \ \overline{C}_{rb;dns} = C_{rb,\min;dns} \ , \text{ for all time } t \geqslant 0 \ ; \tag{4.37b}$$

$$\text{if } \overline{C}_{rb;dns} > C_{rb,\max;dns} \ : \ \overline{C}_{rb;dns} = C_{rb,\max;dns} \ , \text{ for all time } t \geqslant 0 \ . \tag{4.37c}$$

Again, the final approximate forms of (1) the upstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;1-½}$ [Eqs. (4.36a), (4.36b), and (4.36c)] and/or (2) the downstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;N+½}$ [Eqs. (4.37a), (4.37b), and (4.37c)] are used only for the computation of the maximum vertical water concentration difference $\overline{\Delta C^{*}_{rw,\max}}$ (Sect. 3.4) in the water layer at the upstream-end boundary enclosure surface at $i - ½ = 1 - ½$ and/or at the downstream-end boundary enclosure surface at $i + ½ = N + ½$. Since the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)] does not include any longitudinal radionuclide transport term, the final approximate forms of (1) the upstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;1-½}$ [Eqs. (4.36a), (4.36b), and (4.36c)] and/or (2) the downstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;N+½}$ [Eqs. (4.37a), (4.37b), and (4.37c)] are not required for eliminating any auxiliary term in the computational system.

It should be emphasized that the approximate formulation of the unknown upstream-end and/or downstream-end conditions based on limited information in the vicinity of a controlled-flow dam or a coastal open end boundary enclosure surface of the main flow channel of a river or an estuary cannot be considered necessarily as reliable and rigorous formulations of the required upstream-end and/or downstream-end boundary conditions for the simulations of the radionuclide concentration conditions in a river or an estuary. Therefore, in applications of the RADONE computer code to site-specific problems, which necessarily must belong to the first class of interior radionuclide release scenarios, the user should consider very carefully all available information about the radionuclide concentration conditions associated with the upstream-end boundary enclosure surface at $i - ½ = 1 - ½$ and/or the downstream-end boundary enclosure surface at $i + ½ = N + ½$ for a controlled-flow dam or for a coastal open end of the main flow channel, before formulating the approximate conditions for (1) the upstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;1-½}$ [Eqs. (3.34a), (3.34b), and (3.34c)], (2) the upstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;1-½}$ [Eqs. (3.36a), (3.36b), and (3.36c)], (3) the downstream-end water concentration of the radionuclide in the water layer $\overline{C}_{rw;N+½}$ [Eqs. (3.35a), (3.35b), and (3.35c)], and (4) the downstream-end bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;N+½}$ [Eqs. (3.36a), (3.36b), and (3.36c)].

4.3.5 Interpolation of End Conditions

The computational algorithm of the RADONE computer code automatically includes the general, second-upwind-differencing technique (Sect. 3.3.2) in determining the computational values of all transportive intrinsic flow variables, channel flow velocity $\overline{V}_x$ and the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, at the upstream-end enclosure surface at $i - ½ = 1 - ½$ and/or at the downstream-end enclosure surface at $i + ½ = N + ½$ of the main flow channel. This determination of the computational values of the transportive intrinsic flow variables is based on the specified or calculated values of (1) upstream-end channel flow rate $\overline{G}_{x;1-½}$ [Eqs. (4.4), (4.16), and (4.26)] and/or (2) downstream-end channel flow rate $\overline{G}_{x;N+½}$ [Eqs. (4.6), (4.18), and (4.27)].

Upstream-end channel flow velocity $\widetilde{V}_{x;1-½}$ is formulated as

$$\widetilde{V}_{x;1-½} = \overline{V}_{x;1-¼} \quad \text{for} \quad \overline{G}_{x;1-½} = \overline{G}_{x;ups}\ 0 \ , \tag{4.38a}$$

$$\widetilde{V}_{x;1-½} = \overline{V}_{x;ups} \quad \text{for} \quad \overline{G}_{x;1-½} = \overline{G}_{x;ups} > 0 \ . \tag{4.38b}$$

Downstream-end channel flow velocity $\widetilde{V}_{x;N+½}$ is formulated as

$$\widetilde{V}_{x;N+½} = \overline{V}_{x,dns} \quad \text{for} \quad \overline{G}_{x;N+½} = \overline{G}_{x;dns} < 0 \ , \tag{4.39a}$$

$$\widetilde{V}_{x;N+½} = \overline{V}_{x;N+¼} \quad \text{for} \quad \overline{G}_{x;N+½} = \overline{G}_{x;dns} \geq 0 \ . \tag{4.39b}$$

Upstream-end water concentration of the radionuclide in the water layer $\widetilde{C}_{rw;1-½}$ is formulated as

$$\widetilde{C}_{rw;1-½} = \overline{C}_{rw;1} \quad \text{for} \quad \overline{G}_{x;1-½} = \overline{G}_{x;ups} \leq 0 \ , \tag{4.40a}$$

$$\widetilde{C}_{rw;1-½} = \overline{C}_{rw;ups} \quad \text{for} \quad \overline{G}_{x;1-½} = \overline{G}_{x;ups} > 0 \ , \tag{4.40b}$$

Downstream-end water concentration of the radionuclide in the water layer $\widetilde{C}_{rw;N+½}$ is formulated as

$$\widetilde{C}_{rw;N+½} = \overline{C}_{rw;dns} \quad \text{for} \quad \overline{G}_{x;N+½} = \overline{G}_{x;dns} < 0 \ , \tag{4.41a}$$

$$\widetilde{C}_{rw;N+½} = \overline{C}_{rw;N} \quad \text{for} \quad \overline{G}_{x;N+½} = \overline{G}_{x;dns} \geq 0 \ . \tag{4.41b}$$

The computational algorithm of the RADONE computer code uses the general, second-upwind-differencing interpolation formulas [Eqs. (4.38a) through (4.41b)] for evaluating the transportive, intrinsic flow variables associated with the convective transport at the upstream-end boundary enclosure surface at $i - ½ = 1 - ½$ and/or at the downstream-end boundary enclosure surface at $i + ½ = N + ½$ of the main flow channel based on (1) the values of the solution variables at the solution locations in the upstream-end element $i - ¼ = 1 - ¼$ and in the upstream-end element $i = 1$ and/or in the downstream-end internal element $i = N$ and in the downstream-end internal half-element $i + ¼ = N + ¼$ and (2) specified upstream-end conditions and/or specified downstream-end conditions of a river or an estuary. The transportive intrinsic flow variables at the upstream-end enclosure surface at $i - ½ = 1 - ½$ and/or at the downstream-end enclosure surface at $i + ½ = N + ½$ are evaluated at every time step of the numerical solution of the discrete-element computational system, consisting of (1) the discrete-element equation for water surface elevation [Eq. (2.1)], (2) discrete-element equations for flow rate [Eqs. (2.2) and (2.3)], and (3) the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)].

4.4 FORMULATION OF SPECIFIED CONDITIONS ASSOCIATED WITH THE MAIN FLOW CHANNEL

The mathematical transport model of the RADONE computer code includes special formulations for incorporating specified input data associated with

1. the direction of the curvilinear longitudinal x-axis of the main flow channel, which is required for the formulation of surface wind stress (Sect. 3.7),
2. the distribution of drainage areas along the curvilinear longitudinal x-axis of the main flow channel, which is included as auxiliary terms in the formulation of the computational discrete-element system (Sect 2.2), and
3. climatological conditions in the geographic region, which are required for the formulation of transport conditions associated with the rainfall on the water surface, rainfall-runoff from the drainage areas and the wind conditions on the water surface, of the main flow channel of a river or an estuary (Sect. 3.7).

4.4.1 Specified Direction of the Curvilinear Longitudinal Axis of the Main Flow Channel

The direction of the curvilinear longitudinal x-axis of the main flow channel is required for determining the components of wind velocity (along the curvilinear longitudinal x-axis of the main flow channel) $\overline{V}_{x,wnd}$ in the formulation of surface wind stress $\overline{J}_{x,srf;l}$ [Eq. (3.81)]. The angle of the direction of the curvilinear longitudinal x-axis of the main flow channel in each element l is specified as a temporally constant value, relative to any arbitrarily specified geographic reference coordinate system (e.g., longitude or latitude), provided that the same geographic reference coordinate system can also be used for specifying the direction of wind in the geographic region of a river or an estuary; that is,

$$\overline{\Theta}_{x,ref;l} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.42}$$

The computational algorithm of the RADONE computer code uses specified input data for the angle $\overline{\Theta}_{x,ref;l}$ of the curvilinear longitudinal x-axis of the main flow channel in each element l in determining the component of wind velocity $\overline{V}_{x,wnd;l}$ along the curvilinear longitudinal x-axis of the main flow channel at each computational time step of the numerical solution.

The present version of the RADONE computer code does not include the small angle of inclination Ω_x of the curvilinear longitudinal x-axis of the main flow channel, relative to the true horizontal axis in the computational form of the discrete-element equations for flow rate [Eqs. (2.2) and (2.3)]. Hence, the arbitrarily specified curvilinear longitudinal x-axis of the main flow channel is assumed to lie in a true horizontal plane. However, this simplification of the computational form of the discrete-element equations for flow rate does not limit the applicability of the RADONE computer code, because:

1. the small angle of inclination Ω_x is, in a sense, included for convenience in specifying the geometric conditions of the main flow channel of an inclined river (or an estuary) and
2. the gravitational body force effect introduced by the small angle of inclination Ω_x in an inclined coordinate system can be readily represented by an equivalent pressure force resulting from the inclined slope of the water surface in a true horizontal coordinate system.

Furthermore, the effect of the small angle of inclination Ω_x can be readily incorporated by the user in the general FORTRAN program of the RADONE computer code (Sect. 6).

4.4.2 Specified Distribution of the Drainage Areas

The spatial distribution (along the curvilinear longitudinal x-axis of the main flow channel) of available drainage area is specified as a set of input data consisting of each temporally constant value of the drainage area $\overline{A}_{drn;i}$ in each element i, based on available information about the drainage basin in the geographic region of a river or an estuary; that is,

$$\overline{A}_{drn;i} = \text{specified, for all time } t \geqslant 0 \tag{4.43}$$

The specified set of data representing the drainage area $\overline{A}_{drn;i}$ in element i eliminates the auxiliary terms of the discrete-element system of equations, consisting of (1) discrete-element equation for water surface elevation [Eq. (2.1)], (2) discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)], and (3) discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)], in all elements i and all half-elements $i - ¼$ and $i + ¼$ of the main flow channel of a river or an estuary.

4.5 SPECIFIED CLIMATOLOGICAL CONDITIONS ASSOCIATED WITH TRANSPORT AT THE WATER SURFACE

The mathematical model of the RADONE computer code considers only the rainfall and wind conditions associated with the transport at the water surface of a river or an estuary. An extensive and detailed submodel for considering all the climatological conditions in the geographic region containing the main flow channel of a river or an estuary is included in the mathematical model of the ESTONE computer code [Eraslan (1983)], which represents the fundamental fast-transient, one-dimensional mathematical model for simulating the hydrodynamic, thermal, and salinity conditions in a controlled river or a tidal estuary.

The present version of the RADONE computer code does not include provisions for incorporating the spatial variations of the climatological conditions along the curvilinear x-axis of the main flow channel. Hence, the formulation of the rainfall and wind conditions is based only on the considerations of the temporal variations of the weather conditions in the overall geographic (climatological) region of the main flow channel, according to plausible techniques for averaging the available local climatological data [e.g., Eraslan, Erhan, and Lin (1981)] from various weather stations and other sources located in the geographic region of a river or an estuary. The specified rainfall and wind conditions representative of the parts of the general weather conditions in the geographic (climatological) region of the main flow channel can be formulated efficiently by considering the sum of two different types of temporal variations:

1. The long-term variations (hourly, daily, weekly, monthly, etc.) of the rainfall and wind conditions can be specified as a set of input data for the different average values of the rainfall and wind conditions, which remain approximately uniform during specified time periods $\Delta t_{srf,p}$ with possibly different durations.
2. The short-term (generally hourly) variations of the rainfall and wind conditions can be specified as a set of input data for the harmonic variations (maximum of two cosine harmonics), consisting of the amplitude, the period, and the lag time (relative to midnight) of the harmonic variation, which remain uniform during the specified time periods $\Delta t_{srf,p}$ with possibly different durations.

The following formulations of specified rainfall and wind conditions incorporate different specified input data for the two different climatological conditions with the same common specified time periods $\Delta t_{srf,p}$ during which all the different specified climatological conditions are assumed to remain approximately uniform in the geographic region of the main flow channel.

Rainfall rate (per unit area) $\bar{g}_{rnf}$ is formulated as

$$\bar{g}_{rnf} = g_{rnf,avg,p} + \sum_{srf,n=1}^{srf,N} \Delta g_{rnf,p,n} \cos\left[\frac{2\pi}{T_{rnf,p,n}}(t - t_{lag,rnf,p,n})\right] ,$$

$$\text{for time } \; t_{srf,p} < t \leqslant t_{srf,p+1} = t_{srf,p} + \Delta t_{srf,p} \; . \tag{4.44}$$

Wind speed $\bar{V}_{wnd}(|\vec{V}_{wnd}|)$ is formulated as

$$\bar{V}_{wnd} = V_{wnd,avg,p} + \sum_{srf,n=1}^{srf,N} \Delta V_{wnd,p,n} \cos\left[\frac{2\pi}{T_{wnd,p,n}}(t - t_{lag,wnd,p,n})\right] ,$$

$$\text{for time } \; t_{srf,p} < t \leqslant t_{srf,p+1} = t_{srf,p} + \Delta t_{srf,p} \; . \tag{4.45}$$

Wind direction $\bar{\Theta}_{wnd,ref}$ is formulated as

$$\bar{\Theta}_{wnd,ref} = \Theta_{wnd,ref,avg,p} + \sum_{srf,n=1}^{srf,N} \Delta\Theta_{wnd,ref,p,n}$$

$$\times \cos\left[\frac{2\pi}{T_{wnd,ref,p,n}}(t - t_{lag,wnd,ref,p,n})\right] ,$$

$$\text{for time } \; t_{srf,p} < t \leqslant t_{srf,p+1} = t_{srf,p} + \Delta t_{srf,p} \; . \tag{4.46}$$

The component of wind velocity $\bar{V}_{x,wnd;i}$ (along the curvilinear longitudinal x-axis of the main flow channel) is formulated based on (1) specified wind speed $\bar{V}_{wnd}$ [Eq. (4.45)] and wind direction (relative to the arbitrarily specified reference coordinate system) $\bar{\Theta}_{wnd,ref}$ [Eq. (4.46)] and (2) specified direction of the curvilinear longitudinal x-axis of the main flow channel (relative to the arbitrarily specified reference coordinate system) $\bar{\Theta}_{x,ref;i}$ [Eq. (4.42)] in element i as

$$\bar{V}_{x,wnd;i} = \bar{V}_{wnd} \cos(\bar{\Theta}_{x,ref;i} - \bar{\Theta}_{wnd,ref}) \; , \tag{4.47}$$

which is assumed to remain uniform within the element, including the upstream half-element $i - ¼$ and the downstream half-element $i + ¼$; that is,

$$\bar{V}_{x,wnd;i-¼} = \bar{V}_{x,wnd;i+¼} = \bar{V}_{x,wnd;i} \; . \tag{4.48}$$

These specified conditions associated with the water surface and drainage flow can be formulated directly based on available information about the climatological conditions in the geographic region of a river or an estuary. In addition, other auxiliary terms in (1) the discrete-element equations for flow rate [Eqs. (2.2) and (2.3)] and (2) the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)] cannot be specified directly based only on data about the climatological conditions. Formulations of the specified conditions for these auxiliary terms, associated with (1) transport conditions at the water surface and (2) transport conditions with the drainage flow, generally require additional information about the physical conditions external to the main flow channel of a river or an estuary. In most applications of the RADONE computer code to the simulation of flow and radionuclide concentration conditions in a river or an estuary, the necessary specifications of these auxiliary terms can be formulated by using simple but plausible assumptions and by considering available data about the climatological conditions in the region.

The specified form of the component of rainfall velocity $\bar{V}_{x,rnf;i}$ (along the curvilinear longitudinal x-axis of the main flow channel) in element i is formulated according to an empirical formula that is based on the assumption that the component of rainfall velocity at the water surface of the main flow channel can be approximated as a specified percentage of wind velocity $\bar{V}_{x,wnd;i}$ (along the curvilinear longitudinal x-axis of the main flow channel):

$$\bar{V}_{x,rnf;i} = C_{rnf,wnd}\bar{V}_{x,wnd;i} \tag{4.49}$$

Considering that the constant $C_{rnf,wnd}$, which represents the ratio of the component of rainfall velocity $\bar{V}_{x,rnf;i}$ to wind velocity $\bar{V}_{x,wnd;i}$ on the water surface, is specified (with a suggested value of 0.4) and because wind velocity $\bar{V}_{x,wnd;i}$ [Eq. (4.47)] is also specified according to (1) specified wind speed $\bar{V}_{wnd}$ [Eq. (4.45)] and wind direction $\bar{\Theta}_{wnd,ref}$ [Eq. (4.46)] and (2) the specified direction of the curvilinear longitudinal x-axis of the main flow channel $\bar{\Theta}_{x,ref;i}$ [Eq. (4.42)], the component of rainfall velocity $\bar{V}_{x,rnf;i}$ [Eq. (4.49)] is automatically specified for specified climatological conditions in the geographic region of a river or an estuary.

The present version of the computational algorithm of the RADONE computer code does not include the effect of momentum transport by drainage inflow into the main flow channel. Hence, the specified form of velocity (along the curvilinear longitudinal x-axis of the main flow channel) of drainage flow into element i, $\bar{V}_{x,drn;i}$ [Eqs. (2.2), (2.3), and (3.16)] is assumed as

$$\bar{V}_{x,drn;i} = 0 \ , \text{ for all time } t \geq 0 \ . \tag{4.50}$$

Because the effect of momentum transport by the drainage flow can be important only for forced, directional (along the curvilinear longitudinal x-axis of the main flow channel) drainage conditions, which may occur at only few specific locations along the curvilinear longitudinal x-axis of the main fl[illegible]channel, these special conditions can be formulated readily, without any loss in generality, by considering them as stream or tributary flow conditions, according to the general formulation of the mathematical model of the RADONE computer code (Sect. 4.6).

The necessary information about (1) the water concentration of the radionuclide in the rainfall $\bar{C}_{rw,rnf}$ [Eqs. (2.4), (2.9), and (3.15)] and (2) the water concentration of the radionuclide associated with the drainage flow $\tilde{C}_{rw,drn;i}$ [Eqs. (2.4), (2.9), and (3.17)] cannot be specified based on available data about the standard climatological conditions in the geographic region of a river or an estuary. Therefore, additional information about the radionuclide concentration conditions in different states (e.g., in contaminated aerosols) in the atmosphere above the water surface and over the surface of the drainage areas of the main flow channel may be needed in order to specify (1) the water concentration of the radionuclide in the rainfall $\bar{C}_{rw,rnf}$ [Eqs. (2.4), (2.9), and (3.15)] and (2) the water concentration of the radionuclide associated with the drainage flow $\tilde{C}_{rw,drn;i}$ [Eqs. (2.4), (2.9), and (3.17)] for a river or an estuary.

In general, unless there occur atmospheric releases of the radionuclide into the atmosphere in the general geographic (climatological) region of a river or an estuary, the radionuclide concentration conditions associated with the rainfall on the water surface and with the drainage flow, resulting from the rainfall-runoff, into the main flow channel can be assumed as negligible.

Water concentration of the radionuclide in the rainfall $\mathcal{C}_{rw,rnf}$, without occurrence of any atmospheric radionuclide release scenario, can be assumed as

$$\mathcal{C}_{rw,rnf} = 0 \ , \ \text{for all time } t \geqslant 0 \ . \tag{4.51}$$

Water concentration of the radionuclide in the drainage flow $\mathcal{C}_{rw,drn;l}$, without occurrence of any atmospheric radionuclide release scenario, can be assumed

$$\mathcal{C}_{rw,drn;l} = 0 \ , \ \text{for all time } t \geqslant 0 \ , \tag{4.52}$$

for drainage flow conditions into the main flow channel (Sect. 3.3.3).

However, the fast-transient, one-dimensional two-layer discrete-element mathematical transport model of the RADONE computer code also includes the necessary capabilities for incorporating, approximately but realistically, the effects of the radionuclide transport into the main flow channel that can result from the rainfall on the water surface and from the rainfall-runoff drainage flow, under contaminated aerosol conditions in the atmosphere, which can occur during and after atmospheric releases of the radionuclide in the general geographic (climatological) region of a river or an estua[illegible]

The general formulation of the water concentration of the radionuclide in the rainfall $\mathcal{C}_{rw,rnf}$ includes both the long-term variations (hourly, daily, weekly, etc.) and the short-term variations (generally hourly), consistent with the general formulations of the climatological conditions, associated with the rainfall rate and the wind conditions, based on specified input data with the same common specified time periods $\Delta t_{srf,p}$ during which all the different specified climatological conditions and the radiologic conditions in the atmosphere are assumed to remain approximately uniform in the geographic (climatological) region of the main flow channel.

Water concentration of the radionuclide in the rainfall $\mathcal{C}_{rw,rnf}$, under conditions of an atmosphere radionuclide release scenario, can be formulated as

$$\mathcal{C}_{rw,rnf} = C_{rw,rnf,avg,p} + \sum_{srf,n=1}^{srf,N} \Delta C_{rw,rnf,p,n}$$

$$\times \cos\left[\frac{2\pi}{\mathrm{T}_{rw,rnf,p,n}}(t - t_{lag,rw,rnf,p,n})\right]$$

$$\text{for time } \ t_{srf,p} < t \leqslant t_{srf,p+1} = t_{srf,p} + \Delta t_{srf,p} \tag{4.53}$$

Considering the fact that drainage flow into the main flow channel results from the rainfall-runoff in the geographic (climatological) region of the river or estuary, in the present version of the RADONE computer code, the water concentration of the radionuclide in the drainage flow $\mathcal{C}_{rw,drn}$ [Eq. (3.17)] is assumed to be the same as the water concentration of the radionuclide in the rainfall $\mathcal{C}_{rw,rnf}$ [Eq. (4.53)]; that is

$$\mathcal{C}_{rw,drn} = \mathcal{C}_{rw,rnf} \ , \ \text{for all time } t \geqslant 0 \ . \tag{4.54}$$

If actual, site-specific information is available for specifying the water concentration of the radionuclide in the drainage flow, associated with subsurface and surface rainfall-runoff from the drainage basin in the geographic (climatological) region of a river or an estuary, the user can readily incorporate the detailed site-specific effect of the contaminated drainage flow into the main flow channel, by modifying the FORTRAN statements that specify the water concentration of the radionuclide in the drainage flow $\overline{C}_{rw,drn}$ in the general computational algorithm of the RADONE computer code (Sect. 6).

The specified climatological drainage flow and radionuclide concentration conditions in the geographic (climatological) region of a river or an estuary that are considered in the formulation of the mathematical model of the RADONE computer code consist of (1) rainfall rate (per unit area) $\overline{g}_{rnf}$ [Eq. (4.44)], (2) wind speed $\overline{V}_{wnd}$ [Eq. (4.45)], (3) wind direction $\overline{\Theta}_{wnd,ref}$ [Eq. (4.46)], (4) longitudinal wind velocity (along the curvilinear longitudinal x-axis of the main flow channel) $\overline{V}_{x,wnd}$ at the location of the center of the element i [Eqs. (4.47) and (4.48)], (5) velocity of rainfall (along the curvilinear longitudinal x-axis of the main flow channel) $\overline{V}_{x,rnf;i}$ on the water surface of the element i [Eq. (4.49)], (6) velocity of drainage flow (along the curvilinear longitudinal x-axis of the main flow channel) $\overline{V}_{x,drn;i}$ into the element i [Eq. (4.50], (7) water concentration of the radionuclide in the rainfall $\overline{C}_{rw,rnf}$ [Eqs. (4.51) and (4.53)], and (8) water concentration of the radionuclide in the drainage flow $\overline{C}_{rw,drn}$ [Eqs. (4.52) and (4.54)]. The final forms of these specified conditions eliminate the associated auxiliary terms in (1) the discrete-element equation for water surface elevation [Eq. (2.1)], (2) the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)], (3) the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)], and (4) the formulation of surface wind stress (along the curvilinear longitudinal x-axis of the main flow channel) $\overline{J}'_{x,srf}$ [Eq. (3.90)] in all elements i and all half-elements $i - ¼$ and $i + ¼$ of the main flow channel.

4.6 SPECIFIED CONDITIONS ASSOCIATED WITH GROUNDWATER SEEPAGE FLOW

The formulation of specified groundwater seepage flow conditions considers both spatially varying (along the curvilinear longitudinal x-axis of the main flow channel) and temporally varying groundwater seepage flow conditions in the geographic (climatological) region of a river or an estuary. Specified groundwater seepage flow conditions are formulated according to the specific forms required by the formulation of the simple but physically realistic groundwater seepage flow submodel of the RADONE computer code (Sect. 3.6).

The specified, temporally constant distribution (along the curvilinear longitudinal x-axis of the main flow channel) of the coefficient of composite ground porosity associated with the formulation of hydrostatic groundwater seepage flux into or out of the main flow channel [Eq. (3.85)] is formulated as specified input data for the coefficient of composite ground porosity $R_{grd,por;i}$ in each element i as

$$R_{grd,por;i} = \text{specified, for all time } t \geq 0 \qquad (4.55)$$

The specified, temporally constant distribution (along the curvilinear longitudinal x-axis of the main flow channel) of the average mean water surface elevation in the groundwater table in the geographic (climatological) region of the main flow channel is formulated as specified input data for average mean water surface elevation in the groundwater table $H_{grd,mwt;i}$ [Eq. (3.85)] for each element i as

$$H_{grd,mwt;i} = \text{specified, for all time } t \geq 0 \qquad (4.56)$$

The specified, temporally constant distribution (along the curvilinear longitudinal x-axis of the main flow channel) of the power of the hydrostatic pressure gradient associated with the formulation of hydrostatic groundwater seepage flux into or out of the main flow channel [Eq. (3.85)] is formulated as specified input data for the power of the hydrostatic pressure gradient $r_{grd;i}$ in each element i as

$$r_{grd;i} = \text{specified, for all time } t \geqslant 0 \tag{4.57}$$

The specified, temporally constant distribution (along the curvilinear longitudinal x-axis of the main flow channel) of the average groundwater seepage flow rate into our out of the main flow channel [Eq. (3.84)] is formulated as specified input data for average groundwater seepage flow rate $\overline{G}_{grd,avg;i}$ in each element i as

$$\overline{G}_{grd,avg;i} = \text{specified, for all time } t \geqslant 0 \tag{4.58}$$

The specified, temporally constant bottom-layer groundwater distribution (along the curvilinear longitudinal x-axis of the main flow channel) factor for determining the groundwater seepage flow rate into or out of the bottom layer of element i of the main flow channel, associated with the radionuclide transport rate into or out of the bottom layer, according to the groundwater seepage flow rate into or out of the main flow channel is formulated as specified input data for the bottom-layer groundwater distribution factor $R_{bl,grd;i}$ [Eq. (3.89)] in element i as

$$R_{bl,grd;i} = \text{specified, for all time } t \geqslant 0 \tag{4.59}$$

The temporal variations of specified groundwater seepage flow conditions are formulated as different specified input data for different groundwater seepage flow conditions with the same common specified time periods $\Delta t_{grd,p}$, during which all different specified groundwater seepage flow conditions are assumed to remain approximately uniform in the geographic (climatological) region of the main flow channel.

The temporal variation of the specified scaling factor $R_{grd,reg}$ [Eq. (3.84)] associated with determining the amount of regional groundwater seepage flow rate into or out of the main flow channel is formulated using specified input data for the specified scaling factor $R_{grd,reg,p}$ in the geographic (climatological) region of the main flow channel during the specified time period $\Delta t_{grd,p}$ as

$$R_{grd,reg} = R_{grd,reg,p} \ , \ \text{for time } t_{grd,p} < t \leqslant t_{grd,p+1} = t_{grd,p} + \Delta t_{grd,p} \tag{4.60}$$

The temporal variation of specified water surface elevation in the groundwater table $H_{grd,hwt}$ [Eq. (3.85)] in the geographic (climatological) region of the main flow channel is formulated based on specified input data for the difference in water surface elevation in the groundwater table $\Delta H_{grd,reg,p}$ relative to the specified temporally constant average mean water surface elevation in the geographic (climatological) region of the main flow channel during the specified time period $\Delta t_{grd,p}$ as

$$H_{grd,hwt;i} = H_{grd,mwt;i} + \Delta H_{grd,reg,p} \ ,$$

$$\text{for time } t_{grd,p} < t \leqslant t_{grd,p+1} = t_{grd,p} + \Delta t_{grd,p} \tag{4.61}$$

The present version of the computational algorithm of the RADONE computer code does not include the effect of momentum transport by groundwater seepage inflow conditions, the specified form of velocity (along the curvilinear longitudinal x-axis of the main flow channel) of groundwater seepage flow into element i [Eqs. (2.2), (2.3), and (3.31a)] is assumed as

$$\tilde{V}_{x,grd;l} = 0 \ , \ \text{for all time} \ t \geqslant 0 \qquad (4.62)$$

The effect of momentum transport by groundwater seepage inflow may be important only for very few special cases when groundwater seepage inflow may be forced and directional (along the curvilinear longitudinal *x*-axis of the main flow channel) at few specific locations along the curvilinear longitudinal *x*-axis of the main flow channel. These special conditions of groundwater seepage flow can be formulated readily, without any loss of generality, by considering them as locally specified stream or tributary flow conditions according to the general formulation of the mathematical model of the RADONE computer code (Sect. 4.6).

The present version of the computational algorithm of the RADONE computer code does not include the effects of the spatial variations (along the curvilinear longitudinal *x*-axis of the main flow channel) of the radionuclide concentration conditions associated with the groundwater seepage flow into the main flow channel, because detailed site-specific information about the radionuclide concentration conditions in the groundwater is generally not available for the geographic (climatological) region, which includes the groundwater drainage subregion of a river of an estuary. However, if actual detailed site-specific information is available for the spatial variation of the radionuclide concentration conditions associated with the groundwater seepage flow into the main flow channel, the formulation of the specified conditions for (1) the water concentration of the radionuclide in the groundwater seepage flow into the water layer $\tilde{C}_{rw,grd,wl}$ and (2) the bottom concentration of the radionuclide in the groundwater seepage flow into the bottom layer $\tilde{C}_{rb,grd,bl}$ can be readily modified by the user to incorporate the effects of the spatial variations of the radionuclide concentration conditions in the groundwater seepage flow in the general FORTRAN program of the RADONE computer code (Sect. 6).

Hence, the temporal variation of the specified water concentration of the radionuclide in the groundwater seepage flow into the water layer of the main flow channel $\tilde{C}_{rw,grd,wl}$ is formulated based on specified input data for approximately constant water concentration values of the radionuclide in the groundwater seepage flow into the water layer of the main flow channel $C_{rw,grd,wl,p}$ in the geographic (climatological) region of the main flow channel during the specified time period $\Delta t_{grd,p}$ as

$$\tilde{C}_{rw,grd,wl} = C_{rw,grd,wl,p} \ ,$$

$$\text{for time} \ t_{grd,p} < t \leqslant t_{grd,p+1} = t_{grd,p} + \Delta t_{grd,p} \ . \qquad (4.63)$$

Similarly, the temporal variation of the specified bottom concentration of the radionuclide in the groundwater seepage flow into the bottom layer $\tilde{C}_{rb,grd,bl}$ into the main flow channel is formulated based on specified input data for the approximately constant bottom concentration of the radionuclide in the groundwater seepage flow into the bottom layer of the main flow channel $C_{rb,grd,bl,p}$ in the geographic (climatological) region of the main flow channel during the specified time period $\Delta t_{grd,p}$ as

$$\tilde{C}_{rb,grd,bl} = C_{rb,grd,bl,p} \ ,$$

$$\text{for time} \ t_{grd,p} < t \leqslant t_{grd,p+1} = t_{grd,p} + \Delta t_{grd,p} \ . \qquad (4.64)$$

The specified conditions associated with the groundwater seepage flow in the geographic (climatological) region of a river or an estuary that are considered in the formulation of the mathematical model of the

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RADONE computer code consists of (1) coefficient of composite ground porosity $R_{grd,por;l}$ [Eq. (4.55)], (2) average mean water surface elevation in the groundwater table $H_{grd,mwt;l}$ [Eq. (4.56)], (3) power of the hydrostatic pressure gradient $r_{grd;l}$ [Eq. (4.57)], (4) average groundwater seepage flow rate $\overline{G}_{grd,avg;l}$ [Eq. (4.58)], (5) bottom-layer groundwater distribution factor $R_{bl,grd;l}$ [Eq. (4.59)], (6) scaling factor associated with determining the amount of regional groundwater seepage flow rate into or out of the main flow channel $R_{grd,reg}$ [Eq. (4.69)], (7) water surface elevation in the groundwater table $H_{grd,hwt;l}$ [Eq. (4.61)], (8) velocity (along the curvilinear longitudinal x-axis of the main flow channel) of the groundwater seepage flow $\overline{V}_{x,grd;l}$ [Eq. (4.62)], (9) water concentration of the radionuclide in the groundwater seepage flow into the water layer $\widetilde{C}_{rw,grd,wl}$ [Eq. (4.63)], and (10) bottom concentration of the radionuclide in the groundwater seepage flow into the bottom layer [Eq. (4.64)]. The final forms of these specified conditions eliminate the associated auxiliary terms in (1) the discrete-element equation for water surface elevation [Eq. (2.1)], (2) the discrete-element equations for channel flow rate [Eqs. (2.2) and (2.3)], (3) the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)], (4) the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)], (5) the formulation of regional groundwater seepage flow rate $\overline{G}_{grd,reg}$ [Eq. (3.84)], and (6) the formulation of hydrostatic groundwater seepage flow flux $\overline{g}_{grd,hwt}$ [Eq. (3.85)] in all elements i and all half-elements $i - ¼$ and $i + ¼$ in the main flow channel.

4.7 SPECIFIED STREAM (TRIBUTARY) CONDITIONS

The computational algorithm of the RADONE computer code is specifically designed to incorporate any number N_{srm} of stream or tributary flows along the curvilinear longitudinal x-axis of the main flow channel of a river or an estuary. The formulation of specified stream or tributary flow conditions considers (1) spatial locations (along the curvilinear longitudinal x-axis of the main flow channel) of the connecting junctions of the streams or tributaries, (2) temporally varying flow conditions of the streams or tributaries controlled by the climatological conditions in the geographic region, and (3) temporally varying radionuclide concentration conditions, associated with the flows of the streams or tributaries controlled by the radionuclide release conditions.

The spatial location (along the curvilinear longitudinal x-axis of the main flow channel) of the connecting junction of a stream or tributary n is specified according to element $i_{srm,n}$, which contains the connecting junction, as

$$i_{srm,n} = \text{specified, for all time } t \geqslant 0 \tag{4.65}$$

The general formulation of specified spatial locations [Eq. (4.65)] can incorporate different streams or tributaries with the common connecting junction in the same element. Hence, the special types of local flow conditions associated with drainage flows (Sect. 4.4) and with groundwater seepage flows (Sect. 4.6) can also be considered as individually specified stream or tributary flows according to the general formulation of specified spatial locations (along the curvilinear longitudinal x-axis of the main flow channel) for streams or tributaries.

The necessary information about the radionuclide concentration conditions in the flows of the streams or tributaries in the geographic (climatological) region of a river or an estuary may not be available for all streams and for all tributaries flowing into the main flow channel. For this reason, two user-specified options, in the form of integer control parameters, are included as input data.

The integer control parameter $J_{rw,srm,n,wl}$ for specifying the water concentration of the radionuclide in the flow of stream or tributary *n* into the water layer of the main flow channel is specified as

$$J_{rw,srm,n,wl} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.66}$$

The user-specified value of the integer control parameter $J_{rw,srm,n,wl}$ for specifying the water concentration of the radionuclide in the flow of stream or tributary *n* into the water layer determines the type of specified input data required for specifying the radionuclide concentration conditions of the inflowing stream or tributary *n* into the water layer of the main flow channel. For the user-specified value of the integer control parameter $J_{rw,srm,n,wl} = 0$ for specifying the water concentration of the radionuclide in the flow of stream or tributary *n* into the water layer, the computational algorithm of the RADONE computer code assumes that the water concentration of the radionuclide for the inflow of stream or tributary *n* is approximately equal to the water concentration of the radionuclide in the water layer in the element of the connecting junction $i = i_{srm,n}$ of the main flow channel. Hence, according to "intensive form" (Sect. 2.3.3) of the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)], the radionuclide transport effect of the inflowing stream or tributary *n* is not included in the computations. On the other hand, for the user-specified value of the integer control parameter $J_{rw,srm,n,wl} = 1$ for specifying the water concentration of the radionuclide in the flow of stream or tributary *n* into the water layer, the computational algorithm of the RADONE computer code uses specified input data for temporally varying conditions of the water concentration of the radionuclide in stream or tributary *n*, flowing into the water layer of the main flow channel, in calculating the radionuclide transport effect associated with inflowing stream or tributary *n* on the conditions of water concentration of the radionuclide in the water layer in the element of the connecting junction $i = i_{srm,n}$ of the main flow channel.

The integer control parameter $J_{rb,srm,n,bl}$ for specifying the bottom concentration of the radionuclide in the flow of stream or tributary *n* into the bottom layer of the main flow channel is specified as

$$J_{rb,srm,n,bl} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.67}$$

Similarly, the user-specified value of the integer control parameter $J_{rb,srm,n,bl}$ for specifying the bottom concentration of the radionuclide in the flow of stream or tributary *n* into the bottom layer determines the type of specified input data required for specifying the radionuclide concentration conditions of the inflowing stream or tributary *n* into the bottom layer of the main flow channel. For the user-specified value of the integer control parameter $J_{rb,srm,n,bl} = 0$ for specifying the bottom concentration of the radionuclide in the flow of stream or tributary *n* into the bottom layer, the computational algorithm of the RADONE computer code assumes that the bottom concentration of the radionuclide for the inflow of stream or tributary *n* is approximately equal to the bottom concentration of the radionuclide in the bottom layer in the element of the connecting junction $i = i_{srm,n}$ of the main flow channel. Hence, according to intensive form (Sect. 2.3.4) of the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)], the radionuclide transport effect of the inflowing stream or tributary *n* is not included in the computations. On the other hand, for the user-specified value of the integer control parameter $J_{rb,srm,n,bl} = 1$ for specifying the bottom concentration of the radionuclide in the flow of stream of tributary *n* into the bottom layer, the computational algorithm of the RADONE computer code uses specified input data for temporally varying conditions of the bottom concentration of the radionuclide in stream or tributary n, flowing into the bottom layer of the main flow channel, in calculating that the radionuclide transport effect associated with inflowing stream or tributary n on the conditions of the condition of bottom concentration of the radionuclide in the bottom layer in the element of the connecting junction $i = i_{srm,n}$ of the main flow channel.

Temporal variations of the specified flow conditions of stream or tributary n into the main flow channel of a river or an estuary are formulated using a set of specified input data for different flow conditions of stream or tributary n, with the same common specified time period $\Delta t_{srm,n,p}$, during which all the different specified flow conditions are assumed to remain approximately uniform.

Flow rate of stream or tributary n is specified as

$$\overline{G}_{srm,n} = G_{srm,n,p} \;,$$

$$\text{for time} \;\; t_{srm,n,p} < t \leqslant t_{srm,n,p+1} = t_{srm,n,p} + \Delta t_{srm,n,p} \;. \qquad (4.68)$$

Velocity (along the curvilinear longitudinal x-axis of the main flow channel) of the flow of stream or tributary n is specified as

$$\overline{V}_{x,srm,n} = V_{x,srm,n,p} \;,$$

$$\text{for time} \;\; t_{srm,n,p} < t \leqslant t_{srm,n,p+1} = t_{srm,n,p} + \Delta t_{srm,n,p} \;. \qquad (4.69)$$

The temporal variations of the specified water concentration of the radionuclide in the flow of stream or tributary n into the water layer of the main flow channel $\widetilde{C}_{rw,srm,n,wl}$ is formulated based on specified input data for approximately constant water concentration values of the radionuclide in the flow of stream or tributary n into the water layer of the main flow channel $C_{rw,srm,n,wl,p}$ during the specified time period $\Delta t_{srm,n,p}$ as

$$\widetilde{C}_{rw,srm,n,wl} = C_{rw,srm,n,wl,p} \;,$$

$$\text{for time} \;\; t_{srm,n,p} < t \leqslant t_{srm,n,p+1} = t_{srm,n,p} + \Delta t_{srm,n,p} \qquad (4.70)$$

Similarly, the temporal variations of the specified bottom concentration of the radionuclide in the flow of stream or tributary n into the bottom layer of the main flow channel $\widetilde{C}_{rb,srm,n,bl}$ is formulated based on specified input data for approximately constant bottom concentration values of the radionuclide in the flow of stream or tributary n into the bottom layer of the main flow channel $C_{rb,srm,n,bl,p}$ during the specified time period $\Delta t_{srm,n,p}$ as

$$\widetilde{C}_{rb,srm,n,bl} = C_{rb,srm,n,bl,p} \;,$$

$$\text{for time} \;\; t_{srm,n,p} < t \leqslant t_{srm,n,p+1} = t_{srm,n,p} + \Delta t_{srm,n,p} \qquad (4.71)$$

According to the generalized, nonspatial, upwind-differencing interpolation (Sect. 3.3.3), specified temporally varying conditions for the intrinsic transportive flow variables associated with the flow of a stream or tributary n are used only for the inflow conditions of the stream or tributary into the main flow channel.

The specified conditions associated with the stream or tributary flow conditions into or out of the main flow channel of a river or an estuary that are considered in the formulation of the mathematical model of the RADONE computer code consist of (1) flow rate of stream or tributary n into or out of the main flow channel $\widetilde{G}_{srm,n}$ [Eq. (4.68)], (2) velocity (along the curvilinear longitudinal x-axis of the main flow channel) of stream or tributary n $\widetilde{V}_{x,srm,n}$ [Eq. (4.69)], (3) water concentration of the radionuclide in the flow of stream or tributary n into the water layer of the main flow channel $\widetilde{C}_{rw,srm,n,wl}$ [Eq. (4.70)], and (4) bottom concentration of the radionuclide in the flow of stream or tributary n into the bottom layer of the main flow channel $\widetilde{C}_{rb,srm,n,bl}$ [Eq. (4.71)]. The computational algorithm of the RADONE computer code internally determines the distribution of the flow rate $\widetilde{G}_{srm,n}$ between the water layer and the bottom layer by considering the specified constant depth of the bottom layer D_{bl} [Eq. (2.16)] according to the assumed self-similar vertical distribution of the velocity conditions (Sect. 3), in the main flow channel. The final forms of these specified conditions eliminate the associated auxiliary terms in (1) the discrete-element equation for water surface elevation [Eq. (2.1)], (2) the discrete-element equations for flow rate [Eqs. (2.2) and (2.3)], (3) the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)], and (4) the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)] in all elements i and all half-elements $i - ¼$ and $i + ¼$ in the main flow channel.

4.8 SPECIFIED PLANT CONDITIONS

The computational algorithm of the RADONE computer code is specifically designed to have all the necessary capabilities for incorporating any number N_{plt} of plants, with wide ranges of specified operational conditions and radionuclide release conditions, along the curvilinear longitudinal x-axis of the main flow channel of a river or an estuary. The generalized formulation of specified plant conditions, including spatial locations (along the curvilinear longitudinal x-axis of the main flow channel), temporally varying operational conditions, and temporally varying radionuclide release conditions, can readily consider any type of intake and discharge conditions associated with power plants, pump storage facilities, water withdrawal facilities, and discharges from commercial and public water treatment systems.

Spatial locations (along the curvilinear longitudinal x-axis of the main flow channel) of the intake and the discharge of plant m are specified according to elements that contain the intake and discharge as

$$i_{int,m} = \text{specified, for all time } t \geqslant 0 \ , \tag{4.72}$$

$$i_{dis,m} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.73}$$

A plant may have more than one intake and/or discharge, depending on its number of different operating units at different locations (along the curvilinear longitudinal x-axis of the main flow channel). For this reason, the generalized formulation of specified plant conditions considers each intake and discharge combination as an individual plant with individually specified locations (along the curvilinear longitudinal x-axis of the main flow channel) according to elements that contain the intake and discharge.

The formulation of specified plant conditions can also consider input data about the approximate vertical location of the intake of power plant m in the main flow channel. Depth of the intake $\overline{D}_{int,m}$ of the plant m is specified as

$$\bar{D}_{int,m} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.74}$$

Depth of the bottom of the channel $\bar{D}_{bot,int,m}$ at the location of the intake of plant *m* is specified as

$$\bar{D}_{bot,int,m} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.75}$$

The specified depth information is used for incorporating the effect of the vertical variation of the water concentration of the radionuclide in the water layer in the main flow channel in determining the water concentration of the radionuclide in the intake flow of plant *m*.

A constant factor $R_{wl,int,m}$ for controlling the water-layer intake flow rate of plant *m*, representing the portion (as percent) of the intake flow, withdrawn from the water layer, into the intake structure, in the element $i = i_{int,m}$, which contains the intake of plant *m*, is specified as

$$R_{wl,int,m} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.76}$$

Similarly, a constant coefficient $k_{rw,int,m}$ for controlling the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant *m*, representing the factor required for determining the effect of the vertical location of the intake structure, relative to the water layer, on the water concentration of the radionuclide in the intake flow withdrawn from the water layer, into the intake structure, in the element $i = i_{int,m}$, which contains the intake of plant *m*, is specified as

$$k_{rw,int,m} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.77}$$

Similarly, another constant coefficient $k_{rb,int,m}$ for controlling the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant *m*, representing the factor required for determining the effect of the vertical location of the intake structure, relative to the bottom layer, on the bottom concentration of the intake flow withdrawn from the bottom layer, into the intake structure, in the element $i = i_{int,m}$, which contains the intake of plant *m*, is specified as

$$k_{rb,int,m} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.78}$$

A constant factor $R_{wl,dis,m}$ for controlling the water layer discharge flow rate of plant *m*, representing the portion (as percent) of the discharge flow discharged into the water layer, from the discharge structure, in the element $i = i_{dis,m}$, which contains the discharge of plant *m*, is specified as

$$R_{wl,dis,m} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.79}$$

Similarly, a constant coefficient $k_{rw,dis,m}$ for controlling the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant *m*, representing the factor required for approximately considering the effects of the design and structural features of the discharge of plant *m*, on the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure, in the element $i = i_{dis,m}$, which contains the discharge of plant *m*, is specified as

$$k_{rw,dis,m} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.80}$$

Similarly, another constant coefficient $k_{rb,dis,m}$ for controlling the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant m, representing the factor required for approximately considering the effects of the design and structural features of the discharge of plant m on the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure, in the element $i = i_{dis,m}$, which contains the discharge of plant m, is specified as

$$k_{rb,dis,m} = \text{specified, for all time } t \geqslant 0 \ . \tag{4.81}$$

Temporal variations of the specified operational conditions and radionuclide release conditions of the different plants are formulated based on different specified conditions during different specified time periods. For each plant m, a specified number $N_{opr,m}$ of time periods $\Delta t_{plt,m,p}$ are considered as durations of the specified operational conditions and radionuclide release conditions during which all the conditions associated with the intake and discharge flows into or out of the water layer and into or out of the bottom layer are assumed to remain approximately uniform.

Because the available information about the operational conditions and radionuclide release conditions are generally different for different plants, five user-specified integer control parameters are considered as user-specified options for specifying the input data for plants.

The first integer control parameter $J_{opr,m}$ for indicating whether or not plant m is operating is specified for each specified time period $\Delta t_{plt,m,p}$ as

$$J_{opr,m} = J_{opr,m,p} \ ,$$

$$\text{for time } \ t_{plt,m} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \ . \tag{4.82}$$

When the user-specified value of the integer control parameter for plant operation $J_{opr,m,p} = 0$, the computational algorithm of the RADONE computer code completely excludes the effect of the operation of plant m in the calculations during the specified time period $\Delta t_{plt,m,p}$. When the user-specified value of the integer control parameter for plant operation $J_{opr,m,p} = 1$, the computational algorithm includes the effects of the operation and radionuclide release conditions of plant m in the calculations, based on specified input data for the specified time period $\Delta t_{plt,m,p}$. Hence, the specified input data for temporal variations of the plant operational conditions and radionuclide release conditions of plant m include the value of the integer parameter for power plant operation $J_{opr,m,p}$ and the additional conditions for the intake and discharge flows and for the radionuclide release conditions of plant m, for at least one specified time period $\Delta t_{plt,m,p}$.

The intake flow rate $\overline{G}_{int,m}$ of plant m, withdrawn from the intake element $i = i_{int,m}$ is specified for each specified time period $\Delta t_{plt,m,p}$ as

$$\overline{G}_{int,m} = G_{int,m,p} \ ,$$

$$\text{for time } \ t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \ . \tag{4.83}$$

Similarly, the intake velocity (along the curvilinear longitudinal x-axis of the main flow channel) $\overline{V}_{x,int,m}$ of plant m, associated with the intake flow, withdrawn from the intake element $i = i_{int,m}$, can be specified for each specified time period $\Delta t_{plt,m,p}$ as

$$\overline{V}_{x,int,m} = V_{x,int,m,p} \ ,$$
$$\text{for time } t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \tag{4.84}$$

The general computational algorithm of the RADONE computer code also includes an automatic modification for the general case of intake flow conditions, with the intake flow rate of plant *m* specified as $G_{int,m,p} < 0$ for a specified time period $\Delta t_{plt,m,p}$, but with unknown intake flow velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) condition for the power plant arbitrarily specified, for convenience, as $V_{x,int,m,p} = 0$ for the specified time period $\Delta t_{plt,m,p}$. For this type of specified intake flow conditions, the computational algorithm of the RADONE computer code automatically uses channel flow velocity conditions in the half-elements as velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the intake flow of power plant *m*.

Intake flow velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) in the half-element $i - ¼$ is determined as

$$\widetilde{V}_{x;int,m} = \overline{V}_{x;i-¼} \ , \text{ for } \overline{G}_{int,m,p} < 0 \ , \text{ in element } i_{int,m} \ ,$$
$$\text{for time } t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \ . \tag{4.85}$$

Intake flow velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) in the half-element $i + ¼$ is determined as

$$\widetilde{V}_{x;int,m} = \overline{V}_{x;i+¼} \ , \text{ for } \overline{G}_{int,m,p} < 0 \ , \text{ in element } i_{int,m} \ ,$$
$$\text{for time } t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \ . \tag{4.86}$$

The portion of the intake flow rate $\overline{G}_{int,m,wl;i}$ of plant *m*, withdrawn from the water layer, in the element $i = i_{int,m}$, which contains the intake of plant *m*, is formulated as

$$\overline{G}_{int,m,wl;i} = R_{wl,int,m}\overline{G}_{int,m} \ . \tag{4.87}$$

Similarly, the portion of the intake flow rate $\overline{G}_{int,m,bl;i}$ of plant *m*, withdrawn from the bottom layer, in the element $i = i_{int,m}$, which contains the intake of plant *m*, is formulated as

$$\overline{G}_{int,m,bl;i} = (1 - R_{wl,int,m})\overline{G}_{int,m} \ . \tag{4.88}$$

The second integer control parameter $J_{rw,int,m}$ for determining the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant *m*, is specified for each specified time period $\Delta t_{plt,m,p}$ as

$$J_{rw,int,m} = J_{rw,int,m,p} \ ,$$
$$\text{for time } t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \tag{4.89}$$

The specified value of water concentration of the radionuclide $\overline{C}_{rw,int,m}$ associated with the intake flow, withdrawn from the water layer into the intake structure of plant *m*, is specified for each specified time period $\Delta t_{plt,m,p}$ as

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$$\overline{C}_{rw,int,m} = C_{rw,int,m,p} \;,$$
$$\text{for time } t_{plt,m,p} < t \leq t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \;. \tag{4.90}$$

The user-specified value of the integer control parameter $J_{rw,int,m}$ for determining the water concentration of the radionuclide in the intake flow of plant m [Eq. (4.89)] establishes the type of formulation used in the calculation of the water concentration of the radionuclide, determined according to the generalized upwind-differencing value, associated with the intake flow of plant m, withdrawn from the water layer in element $i = i_{int,m}$, which contains the intake of plant m.

For the user-specified value of the integer control parameter $J_{rw,int,m} = 0$, the computational algorithm of the RADONE computer code internally calculates the water concentration conditions associated with the intake flow of plant m based on the water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ that exists in the element $i = i_{int,m}$, which contains the intake of plant m, by utilizing all the available information about the effect of the vertical variation of the water concentration of the radionuclide in the water layer and the vertical location of the structure of the intake of plant m.

First, vertically local water concentration of the radionuclide in the water layer at the specified depth of the intake $\overline{C}_{rw,int,D,m;i}$ is calculated approximately based on (1) the specified depth of the intake $D_{int,m}$ and (2) the specified depth of the bottom of the channel $D_{bot,int,m}$ at the location of the intake of plant m, according to the combined self-similar form of the vertical and lateral variation of the water concentration of the radionuclide in the water layer $C_{rw}(y,\eta)$ [Eqs. (3.35a) and (3.35b)] over the cross section of the element $i = i_{int,m}$, which contains the intake of plant m, as

$$\overline{C}_{rw,int,D,m;i} = \left\{ \overline{C}_{rw} + \frac{\overline{\Delta C}^{*}_{rw,\max}}{2} \frac{\overline{B}_{srf}\langle D^2 \rangle}{\overline{A} D_{\max}} \right.$$
$$\left. \times \left[1 - \frac{2\overline{A}}{\overline{B}_{srf}\langle D^2 \rangle} D_{bot,int,m} \left(3\eta^2_{int,m} - 2\eta^3_{int,m} \right) \right] \right\}_{i=i_{int,m}} \;, \tag{4.91}$$

where the vertical similarity variable $\eta_{int,m}$ of the cross section of the main flow channel [Eq. (3.29)] is defined as

$$\eta_{int,m} = \frac{D_{int,m}}{D_{bot,int,m}} \;. \tag{4.92}$$

The actual upwind-differenced transportive value of the water concentration of the radionuclide in the intake flow $\widetilde{C}_{rw,int,m,wl;i}$ of plant m is formulated, based on (1) water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element $i = i_{int,m}$, which contains the intake of plant m, (2) vertically local water concentration of the radionuclide in the water layer at the location of the intake structure $\overline{C}_{rw,int,D,m;i}$ [Eq. (4.91)] of plant m, and (3) the specified constant coefficient $k_{rw,int,m}$ [Eq. (4.77)] for controlling the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant m, as

$$\widetilde{C}_{rw,int,m,wl;i} = (1 - k_{rw,int,m})\overline{C}_{rw;i} + k_{rw,int,m}\overline{C}_{rw,int,D,m;i} \;, \tag{4.93a}$$

which can also be represented as

$$\overline{C}_{rw,int,m,wl;i} = \overline{C}_{rw;i} + k_{rw,int,m}\left\{\frac{\overline{\Delta C}^{*}_{rw,\max}}{2}\frac{\overline{B}_{srf}\langle D^2\rangle}{\overline{AD}_{\max}}\right.$$

$$\left.\times\left[1 - \frac{2\overline{A}}{\overline{B}_{srf}\langle D^2\rangle} D_{bot,int,m}(3\eta^2_{int,m} - 2\eta^3_{int,m})\right]\right\}_{i=i_{int,m}} . \qquad (4.93b)$$

Alternately, for the user-specified value of the integer control parameter $J_{rw,int,m} = 1$, the computational algorithm of the RADONE computer code directly uses the specified input data as the value of the water concentration of the radionuclide $\overline{C}_{rw,int,m}$, associated with the intake flow, withdrawn from the water layer, into the intake structure of plant m [Eq. (4.90)], for the upwind-differenced transportive value of the water concentration of the radionuclide in the intake flow $\widetilde{\overline{C}}_{rw,int,m,wl;i}$ of plant m, withdrawn from the water layer, in element $i = i_{int,m}$, which contains the intake of plant m, as

$$\overline{C}_{rw,int,m,wl;i} = \overline{C}_{rw,int,m} \ , \ \text{for } i = i_{int,m} \ . \qquad (4.94)$$

The third integer control parameter $J_{rb,int,m}$ for determining the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant m, is specified for each specified time period $\Delta t_{plt,m,p}$ as

$$J_{rb,int,m} = J_{rb,int,m,p} \ ,$$
$$\text{for time } t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \ . \qquad (4.95)$$

The specified value of bottom concentration of the radionuclide $\overline{C}_{rb,int,m}$ associated with the intake flow, withdrawn from the bottom layer, into the intake structure of plant m, is specified for each specified time period $\Delta t_{plt,m,p}$ as

$$\overline{C}_{rb,int,m} = C_{rb,int,m,p} \ ,$$
$$\text{for time } t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \ . \qquad (4.96)$$

Again, the user-specified value of the integer control parameter $J_{rb,int,m}$ for determining the bottom concentration of the radionuclide in the intake flow of plant m [Eq. (4.95)] establishes the type of formulation used in the calculation of the bottom concentration of the radionuclide, determined according to the generalized upwind-differenced value, associated with the intake flow of plant m, withdrawn from the bottom layer in element $i = i_{int,m}$, which contains the intake of plant m.

For the user-specified value of the integer control parameter $J_{rb,int,m} = 0$, the computational algorithm of the RADONE computer code internally calculates the actual upwind-differenced transportive value of the bottom concentration of the radionuclide in the intake flow $\widetilde{\overline{C}}_{rb,int,m,bl;i}$ of plant m, based on (1) the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element $i = i_{int,m}$, which contains the intake of plant m, and (2) the specified constant coefficient $k_{rb,int,m}$ [Eq. (4.78)] for controlling the bottom concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant m, as

$$\overline{C}_{rb,int,m,bl;i} = k_{rb,int,m}\overline{C}_{rb;i} \ . \qquad (4.97)$$

Alternately, for the user-specified value of the integer control parameter $J_{rb,int,m} = 1$, the computational algorithm of the RADONE computer code directly uses the specified input data as the value of the bottom concentration of the radionuclide $\overline{C}_{rb,int,m}$, associated with the intake flow withdrawn from the bottom layer, into the intake structure of plant m [Eq. (4.96)], for the upwind-differenced transportive value of the bottom concentration of the radionuclide in the intake flow $\widetilde{C}_{rb,int,m,bl;i}$ of plant m, withdrawn from the bottom layer, in element $i = i_{int,m}$, which contains the intake of plant m, as

$$\widetilde{C}_{rb,int,m,bl;i} = \overline{C}_{rb,int,m} \quad , \text{ for } \; i = i_{int,m} \quad . \tag{4.98}$$

The discharge flow rate $\overline{G}_{dis,m}$ of plant m, discharged into the discharge element $i = i_{dis,m}$ is specified for each specified time period $\Delta t_{plt,m,p}$ as

$$\begin{gathered} \overline{G}_{dis,m} = G_{dis,m,p} \quad , \\ \text{for time } \; t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \quad . \end{gathered} \tag{4.99}$$

Similarly, the discharge velocity (along the curvilinear longitudinal x-axis of the main flow channel) $\overline{V}_{x,dis,m}$ of plant m, associated with the discharge flow, discharged into the element $i = i_{dis,m}$, can be specified for each specified time period $\Delta t_{plt,m,p}$ as

$$\begin{gathered} \overline{V}_{x,dis,m} = V_{x,dis,m,p} \quad , \\ \text{for time } \; t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \quad . \end{gathered} \tag{4.100}$$

The portion of the discharge flow rate $\overline{G}_{dis,m,wl;i}$ of plant m, discharged into the water layer, in the element $i = i_{dis,m}$, which contains the discharge of plant m, is formulated as

$$\overline{G}_{dis,m,wl;i} = R_{wl,dis,m}\overline{G}_{dis,m} \quad . \tag{4.101}$$

Similarly, the portion of the discharge flow rate $\overline{G}_{dis,m,bl;i}$ of plant m, discharged into the bottom layer, in the element $i = i_{dis,m}$, which contains the discharge of plant m, is formulated as

$$\overline{G}_{dis,m,bl;i} = (1 - R_{wl,dis,m})\overline{G}_{dis,m} \quad . \tag{4.102}$$

The fourth integer control parameter $J_{rw,dis,m}$ for determining the water concentration of the radionuclide in the discharge, discharged into the water layer, is specified for each specified time period $\Delta t_{plt,m,p}$ as

$$\begin{gathered} J_{rw,dis,m} = J_{rw,dis,m,p} \quad , \\ \text{for time } \; t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \quad . \end{gathered} \tag{4.103}$$

The specified input data for the temporal variations of the water concentration of the radionuclide associated with the discharge flow $C_{rw,dis,m,p}$, during different specified time periods $\Delta t_{plt,m,p}$, of plant m represent two distinctly different radionuclide release conditions, into the water layer, depending on the user-specified value of the integer control parameter $J_{rw,dis,m}$ for determining the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure, of plant m [Eq. (4.103)].

For the user-specified value of the integer control parameter $J_{rw,dis,m}$, $= 0$, the specified input data for the temporal variation of the water concentration of the radionuclide associated with the discharge flow $C_{rw,dis,m,p}$, during the specified time period $\Delta t_{plt,m,p}$, of plant m represent the additional radionuclide release into the circulating water system, discharging into the water layer, in the form of radionuclide concentration rise $\overline{\Delta C}_{rw,plt,m}$, which occurs in plant m, during the specified time period $\Delta t_{plt,m,p}$ as

$$\overline{\Delta C}_{rw,plt,m} = C_{rw,dis,m,p} \ , \text{ for } J_{rw,dis,m} = 0 \ ,$$
$$\text{for time } t_{plt,m,p} < t \leq t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \ . \tag{4.104}$$

Consequently, the actual transportive value of the water concentration of the radionuclide in the discharge flow $\widetilde{C}_{rw,dis,m,wl;i}$ of plant m is formulated, based on (1) actual upwind-differenced value of the water concentration of the radionuclide in the intake flow $\widetilde{C}_{rw,int,m,wl;i}$ of plant m [Eqs. (4.93a) and (4.93b)], (2) specified radionuclide concentration rise $\overline{\Delta C}_{rw,plt,m}$ that occurs in plant m [Eq. (4.104)], and (3) specified constant coefficient $k_{rw,dis,m}$ for controlling the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant m [Eq. (4.80)], as

$$\widetilde{C}_{rw,dis,m,wl;i} = k_{rw,dis,m}(\widetilde{C}_{rw,int,m,wl;i} + \overline{\Delta C}_{rw,plt,m}) \ . \tag{4.105}$$

Alternately, for the user-specified value of the integer control parameter $J_{rw,dis,m} = 1$, the specified input data for the temporal variation of the water concentration of the radionuclide associated with the discharge flow $C_{rw,dis,m,p}$, during the specified time period $\Delta t_{plt,m,p}$, of plant m, represents the specified value of the water concentration of the radionuclide in the discharge flow $\widetilde{C}_{rw,dis,m}$, discharged into the water layer, from the discharge structure of plant m, as

$$\widetilde{C}_{rw,dis,m} = C_{rw,dis,m,p} \ , \text{ for } J_{rw,dis,m} = 1 \ ,$$
$$\text{for time } t_{plt,m,p} < t \leq t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \ . \tag{4.106}$$

Consequently, the transportive value of the water concentration of the radionuclide in the discharge flow $\widetilde{C}_{rw,dis,m,wl;i}$ of plant m is determined directly, based on (1) specified value of water concentration of the radionuclide in the discharge flow $\widetilde{C}_{rw,dis,m}$, discharged into the water layer, from the discharge structure of plant m [Eq. (4.106)], and (2) specified constant coefficient $k_{rw,dis,m}$ for controlling the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant m [Eq. (4.80)], as

$$\widetilde{C}_{rw,dis,m,wl;i} = k_{rw,dis,m}\widetilde{C}_{rw,dis,m} \tag{4.107}$$

The fifth integer control parameter $J_{rb,dis,m}$ for determining the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, is specified for each specified time period $\Delta t_{plt,m,p}$ as

$$J_{rb,dis,m} = J_{rb,dis,m,p} \ ,$$
$$\text{for time } t_{plt,m,p} < t \leq t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \tag{4.108}$$

Again, the specified input data for the temporal variations of the bottom concentration of the radionuclide associated with the discharge flow $C_{rb,dis,m,p}$, during different specified time periods $\Delta t_{plt,m,p}$, of plant m represent two distinctly different radionuclide release conditions, into the bottom layer, depending on the user-specified value of the integer control parameter $J_{rb,dis,m}$ for determining the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure, of plant m [Eq. (4.108)].

For the user-specified value of the integer control parameter $J_{rb,dis,m} = 0$, the specified input data for the temporal variation of the bottom concentration of the radionuclide associated with the discharge flow $C_{rb,dis,m,p}$, during the specified time period $\Delta t_{plt,m,p}$, of plant m represents the additional radionuclide release into the circulating water system, discharging into the bottom layer, in the form of radionuclide concentration rise $\overline{\Delta C}_{rb,plt,m}$, which occurs in plant m, during the specified time period $\Delta t_{plt,m,p}$ as

$$\overline{\Delta C}_{rb,plt,m} = C_{rb,dis,m,p} \ , \ \text{for} \ J_{rb,dis,m} = 0 \ ,$$
$$\text{for time} \ t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \ . \tag{4.109}$$

Consequently, the transportive value of the bottom concentration of the radionuclide in the discharge flow $\tilde{C}_{rb,dis,m,wl;i}$ of plant m is formulated, based on (1) actual upwind-differenced value of the bottom concentration of the radionuclide in the intake flow $\tilde{C}_{rb,int,m,bl;i}$ of plant m [Eq. (4.97)], (2) specified radionuclide concentration rise $\overline{\Delta C}_{rb,plt,m}$, which occurs in plant m [Eq. (4.109)], and (3) specified constant coefficient $k_{rb,dis,m}$ for controlling the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant m [Eq. (4.81)], as

$$\tilde{C}_{rb,dis,m,bl;i} = k_{rb,dis,m}(\tilde{C}_{rb,int,m,bl;i} + \overline{\Delta C}_{rb,plt,m}) \ . \tag{4.110}$$

Alternately, for the user-specified value of the integer control parameter $J_{rb,dis,m} = 1$, the specified input data for the temporal variation of the bottom concentration of the radionuclide associated with the discharge flow $C_{rb,dis,m,p}$, during the specified time period $\Delta t_{plt,m,p}$, of plant m, represents the specified value of the bottom concentration of the radionuclide in the discharge flow $\tilde{C}_{rb,dis,m}$, discharged into the bottom layer, from the discharge structure of plant m, as

$$\tilde{C}_{rb,dis,m} = C_{rb,dis,m,p} \ , \ \text{for} \ J_{rb,dis,m} = 1 \ ,$$
$$\text{for time} \ t_{plt,m,p} < t \leqslant t_{plt,m,p+1} = t_{plt,m,p} + \Delta t_{plt,m,p} \ . \tag{4.111}$$

Consequently, the transportive value of the bottom concentration of the radionuclide in the discharge flow $\tilde{C}_{rb,dis,m,bl;i}$ of plant m is determined directly, based on (1) specified value of bottom concentration of the radionuclide in the discharge flow $\tilde{C}_{rb,dis,m}$, discharged into the bottom layer, from the discharge structure of plant m [Eq. (4.111)] and (2) specified constant coefficient $k_{rb,dis,m}$ for controlling the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant m [Eq. (4.80)], as

$$\tilde{C}_{rb,dis,m,bl;i} = k_{rb,dis,m}\tilde{C}_{rb,dis,m} \ . \tag{4.112}$$

It is important to point out that the general formulation of the specified plant conditions provides to the user an extensive capability for modeling accurately the temporally detailed and spatially detailed radionuclide release conditions from different plants along the main flow channel of a river or an estuary.

Therefore, the computational algorithm of the RADONE computer code includes all the necessary capabilities for simulating the outcome of any actual or hypothetical radionuclide release scenario that occurs in a river or an estuary. On the other hand, it is also important to point out that in applications of the RADONE computer code to the simulation of the radionuclide concentration conditions in a river or an estuary, when accurate and detailed modeling of the radionuclide release conditions from plants is not an important issue, the general formulation of the specified plant conditions, associated with the radionuclide uptake and release conditions at the intakes and discharges, respectively, can be readily simplified by assigning the values of either 0 (zero) or 1 to the appropriate parameters and coefficients used in the specification of the intake and discharge conditions.

Specified operational conditions and radionuclide release conditions, associated with the plants along the main flow channel of a river or an estuary, consist of (1) intake flow rate $\overline{G}_{int,m}$ of plant *m* [Eq. (4.83)], (2) velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the intake flow $\overline{V}_{x,int,m}$ of plant *m* [Eqs. (4.84), (4.85), and (4.86)], (3) portion of the intake flow rate $\overline{G}_{int,m,wl;i}$ of plant *m*, withdrawn from the water layer, in element $i = i_{int,m}$, which contains the intake of plant *m* [Eq. (4.87)], (4) upwind-differenced, transportive value of water concentration of the radionuclide in the intake flow $\widetilde{C}_{rw,int,m,wl;i}$ of plant *m*, withdrawn from the water layer, into the intake structure in element $i = i_{int,m}$, which contains the intake of plant *m* [Eqs. (4.93a), (4.93b), and (4.94)], (5) portion of the intake flow rate $\overline{G}_{int,m,bl;i}$ of plant *m*, withdrawn from the bottom layer, in element $i = i_{int,m}$, which contains the intake of plant *m* [Eq. (4.88)], (6) upwind-differenced, transportive value of bottom concentration of the radionuclide in the intake flow $\widetilde{C}_{rb,int,bl,m;i}$ of plant *m*, withdrawn from the bottom layer, into the intake structure in element $i = i_{int,m}$, which contains the intake of plant *m* [Eqs. (4.97) and (4.98)], (7) discharge flow rate $\overline{G}_{dis,m}$ of plant *m* [Eq. (4.99)], (8) velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the discharge flow $\overline{V}_{x,dis,m}$ of plant *m* [Eq. (4.100)], (9) portion of the discharge flow rate $\overline{G}_{dis,m,wl;i}$ of plant *m*, discharged into the water layer, in element $i = i_{dis,m}$, which contains the discharge of plant *m* [Eq. (4.101)], (10) transportive value of the water concentration of the radionuclide in the discharge flow $\overline{C}_{rw,dis,m,wl;i}$ of plant *m*, discharged into the water layer, from the discharge structure, in element $i = i_{dis,m}$, which contains the discharge of plant *m* [Eqs. (4.105) and (4.107)], (11) portion of the discharge flow rate $\overline{G}_{dis,m,bl;i}$ of plant *m*, discharged into the bottom layer, in element $i = i_{dis}$, which contains the discharge of plant *m* [Eq. (4.102)], and (12) transportive value of bottom concentration of the radionuclide in the discharge flow $\overline{C}_{rb,dis,m,bl;i}$ of plant *m*, discharged into the bottom layer, from the discharge structure, in element $i = i_{dis,m}$, which contains the discharge of plant *m* [Eqs. (4.110) and (4.112)].

The final specified forms of these operational conditions and radionuclide release conditions eliminate the auxiliary terms in (1) the discrete-element equation for water surface elevation [Eq. (2.1)], (2) the discrete-element equations for flow rate [Eqs. (2.2) and (2.3)], (3) the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)], and (4) the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)] in all elements *i* and all half-elements $i - ¼$ and $i + ¼$ in the main flow channel.

4.9 OPTIONAL SPECIFIED CONDITIONS FOR WATER SURFACE ELEVATION AND CHANNEL FLOW RATE

The general computational algorithm of the RADONE computer code includes a user-specified option for excluding the solution of hydrodynamic conditions by incorporating already computed and stored results of water surface elevation $\overline{H}_i$ in element *i* and channel flow rates $\overline{G}_{x;i-¼}$ in the upstream half-element

$i - \frac{1}{4}$ and $\overline{G}_{x;i+\frac{1}{4}}$ in the downstream half-element $i + \frac{1}{4}$. This option, which is common to all associated computer codes of the fast-transient, one-dimensional mathematical transport models of the UTA project [e.g., ESTONE computer code, Eraslan (1983)], is specifically designed to minimize the computer cost in the applications of the RADONE computer code to simulate the radionuclide concentration conditions in an actual river or an estuary with known (or already calculated) hydrodynamic conditions.

This special option of the RADONE computer code is included for two reasons. First, considering the general physical characteristics of the main flow channel of a typical controlled river or a tidal estuary, the computational solution of the hydrodynamic conditions, consisting of water surface elevation $\overline{H}_i$ in element i and channel flow rates, $\overline{G}_{x;i-\frac{1}{4}}$ in the upstream half-element $i - \frac{1}{4}$ and $\overline{G}_{x;i+\frac{1}{4}}$ in the downstream half-element $i + \frac{1}{4}$, generally requires substantially smaller computational time steps (hence, substantially longer computer time) to guarantee the stability of the numerical integration than those required by the computational solution of the water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ and the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i, for a radionuclide with reasonably slow radiological decay characteristics (Sect. 5). Second, in applications of the RADONE computer code to the assessment of the radiological impact of actual or hypothetical scenarios associated with routine or accidental radionuclide release conditions from single or multiple plants and from other sources distributed along a controlled river or a tidal estuary, it usually becomes necessary to consider numerous different plant operational conditions and radionuclide release conditions at different plants and at other sources for approximately the same hydrodynamic conditions in the main flow channel. For these repeated applications, it usually becomes unnecessary to include the same repeated solutions of water surface elevation $\overline{H}_i$ in element i and channel flow rates, $\overline{G}_{x;i-\frac{1}{4}}$ in the upstream half-element $i - \frac{1}{4}$ and $\overline{G}_{x;i+\frac{1}{4}}$ in the downstream half-element $i + \frac{1}{4}$, in the numerical solutions of water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ and the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i for simulating the different required radionuclide concentration conditions along the river or estuary.

The formulation of optional specified conditions for water surface elevation $\overline{H}_i$ in element i and channel flow rate $\overline{G}_{x;i-\frac{1}{4}}$ in the upstream half-element $i - \frac{1}{4}$ and $\overline{G}_{x;i+\frac{1}{4}}$ in the downstream half-element $i + \frac{1}{4}$ is specifically designed to incorporate directly, without any modification, the output results of the RADONE computer code [or the ESTONE computer code, Eraslan (1983)] for the hydrodynamic conditions. Hence, the formulation of optional specified hydrodynamic conditions considers the equally incremented format of specified input data with temporally constant values for the specified time period $\Delta t_{hyd,p}$, between the specified times $t_{hyd,p}$ and $t_{hyd,p+1}$, of the input data sets for water surface elevation $H_{i,p}$ in element i and channel flow rates $G_{x;i-\frac{1}{4},p}$ in the upstream half-element $i - \frac{1}{4}$ and $G_{x;i+\frac{1}{4},p}$ in the downstream half-element $i + \frac{1}{4}$.

Input data [illegible] water surface elevation $H_{i,p}$ are specified as

$$H_{i,p} = \text{specified at time } t_{hyd,p} \ . \tag{4.113}$$

Input data for the channel flow rates $G_{x;i-\frac{1}{4},p}$ and $G_{x;i+\frac{1}{4},p}$ are specified as

$$G_{x;i-\frac{1}{4},p} = \text{specified at time } t_{hyd,p} \ , \tag{4.114a}$$

$$G_{x;i+\frac{1}{4},p} = \text{specified at time } t_{hyd,p} \ . \tag{4.114b}$$

The hydrodynamic conditions at every computational time step of the numerical solution are determined based on linear interpolation of optional specified input data for the hydrodynamic conditions as

$$\overline{H}_i = H_{i,p} + \frac{(t - t_{hyd,p})}{\Delta t_{hyd}}(H_{i,p+1} - H_{i,p}) \ ,$$

$$\text{for time } \ t_{hyd,p} < t \leqslant t_{hyd,p+1} = t_{hyd,p} + \Delta t_{hyd} \ ; \qquad (4.115)$$

$$\overline{G}_{x;i-\frac{1}{4}} = G_{x;i-\frac{1}{4},p} + \frac{(t - t_{hyd,p})}{\Delta t_{hyd}}(G_{x;i-\frac{1}{4},p+1} - G_{x;i-\frac{1}{4},p}) \ ,$$

$$\text{for time } \ t_{hyd,p} < t \leqslant t_{hyd,p+1} = t_{hyd,p} + \Delta t_{hyd} \ , \qquad (4.116a)$$

$$\overline{G}_{x;i+\frac{1}{4}} = G_{x;i+\frac{1}{4},p} + \frac{(t - t_{hyd,p})}{\Delta t_{hyd}}(G_{x;i+\frac{1}{4},p+1} - G_{x;i+\frac{1}{4},p}) \ ,$$

$$\text{for time } \ t_{hyd,p} < t \leqslant t_{hyd,p+1} = t_{hyd,p} + \Delta t_{hyd} \ . \qquad (4.116b)$$

The optional specified conditions determine (1) water surface elevation $\overline{H}_i$ in element i [Eq. (4.115)], (2) channel flow rate $\overline{G}_{x;i-\frac{1}{4}}$ in the upstream half-element $i - \frac{1}{4}$ [Eq. (4.116a)], and (3) channel flow rate $\overline{G}_{x;i+\frac{1}{4}}$ in the downstream half-element $i + \frac{1}{4}$ [Eq. (4.116b)].

According to the standard general computational algorithm of ESTONE, the final linearly interpolated forms of these optional hydrodynamic conditions provide all the necessary information for the solution of (1) the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)] and (2) the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)] in all elements i of the main flow channel of a river or an estuary.

4.10 DISCUSSION OF SPECIFIED TRANSPORT CONDITIONS

The one-dimensional, discrete-element, mathematical transport model of the RADONE computer code is specifically formulated to include the necessary capabilities for incorporating accurately all detailed, site-specific, temporal, and spatial variations of (1) climatological and geophysical conditions in the geographic region, (2) plant operational conditions, and (3) radionuclide release conditions associated with all possible radiological problems, which collectively control the hydrodynamic and radionuclide concentration conditions in a controlled river or a tidal estuary. Hence, the computational algorithm of RADONE can readily incorporate large amounts of specified input data for the available detailed site-specific information to determine accurately the mass, momentum, and radionuclide transport across the boundary enclosure surfaces of the main flow channel of a river or an estuary. The special capabilities for incorporating large amounts of detailed site-specific data were specifically developed to guarantee that the fast-transient, one-dimensional, discrete-element transport model of the RADONE computer code can be used, without major restrictions, to predict accurately the hydrodynamic and radionuclide concentration conditions in an actual controlled-flow river or an actual tidal-dominated estuary which occur during and after any actual or hypothetical scenario associated with routine or accidental radionuclide release conditions into the main flow channel.

It is extremely important for the user to understand that application of the RADONE computer code does not always require large amounts of detailed input data for specified transport conditions. Indeed, the RADONE computer code can be implemented in simulating the hydrodynamic and radionuclide concentration conditions in a river or an estuary with a minimal amount of site-specific information about specified transport conditions by using the following three user-specified options for considering simple sets of specified input data:

1. The general computational algorithm of the RADONE computer code includes special user-specified integer control parameters for completely eliminating the need for certain input data sets associated with the specification of transport conditions at certain boundary enclosure surfaces of the main flow channel (see Sect. 6 for detailed discussions). If the value of the integer control parameter for a set of specified transport conditions is specified as zero by the user, the general computational algorithm of the RADONE computer code automatically excludes the effect of the particular set of transport conditions in the computations; hence, it automatically eliminates the need for any specified input data for the particular set of the transport conditions.
2. In applications that require only simple, temporally constant specified transport conditions, the general computational algorithm of the RADONE computer code can readily eliminate the need for specified input data sets for temporally varying specified transport conditions. The user can specify a single specified time period, longer than the required duration of the simulation, with a single set of input data for a set of specified transport conditions at any boundary enclosure surface of the main flow channel. Under these conditions, the general computational algorithm of the RADONE computer code automatically assumes temporally constant specified transport conditions at the particular boundary enclosure surface; hence, it automatically eliminates the need for any additional input data for the particular set of specified transport conditions.
3. The general computational algorithm of the RADONE computer code includes, for convenience only, special formulations of various specified transport conditions in terms of harmonic variations with specified input data sets for the amplitude, period, and lag time (relative to midnight) of each harmonic. In applications that do not require harmonic variations, the user-specified value of zero for the number of harmonics (or 1 for the number of harmonics with zero amplitude) automatically eliminates the need for any additional specified input data for the harmonic variations of particular specified transport conditions at the particular boundary enclosure surface of the main flow channel.

Hence, the amount of specified input data required in any application of the RADONE computer code depends solely on the user's decision regarding requirements of the level of accuracy and detail of (1) site-specific information about the geophysical and climatological conditions in the geographic region, (2) information about the plant operational conditions, and (3) radionuclide release conditions, associated with all possible actual or hypothetical routine or accidental radionuclide release scenarios, which collectively determine the level of accuracy of the results of computer simulations of the hydrodynamic and radionuclide concentration conditions in the main flow channel of a controlled-flow river or a tidal-dominated estuary.

In summary, the RADONE computer code can be implemented, either with extremely simple input data sets or with extensive, accurate, and detailed input data sets for the specified transport conditions, depending only on the choice of the user, for simulating the hydrodynamic and/or radionuclide concentration conditions in a river or an estuary.

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5. SUMMARY OF COMPUTATIONAL PROCEDURE AND STABILITY CRITERIA OF NUMERICAL SOLUTION METHOD OF RADONE COMPUTER CODE

The development of the computational algorithm of the fast-transient, one-dimensional, two-layer, discrete-element radionuclide transport model; and its associated RADONE computer code is based on the applications of the fundamental computational concepts of the Unified Transport Approach (UTA) [Eraslan et al. (1976), Eraslan and Witten (1984)], which utilize stable numerical integration techniques for the solution of spatially discretized systems of simultaneous, coupled, first-order differential equations, which must be considered in conjunction with the sets of algebraic constraint equations that collectively represent the closure of the mathematical transport model. The detailed development of the fundamental computational concepts for the fast-transient, one-dimensional, discrete-element transport models for controlled rivers and tidal estuaries is presented in the users manual of the ESTONE computer code [Eraslan (1983)]. Therefore, the subsequent development of the computational procedure for the numerical solution of the governing systems of discrete-element equations of the fast-transient, one-dimensional, discrete-element radionuclide transport model of the RADONE computer code will only present the summary considerations of the fundamental computational concepts of UTA [Eraslan et al. (1976), Eraslan and Witten (1984)] and the stability criteria of the numerical solutions.

5.1 ADDITIONAL DEFINITIONS OF MATHEMATICAL VARIABLES ASSOCIATED WITH COMPUTATIONAL PROCEDURE AND STABILITY CRITERIA

The additional auxiliary variables of the fast-transient, one-dimensional, two-layer, discrete-element radionuclide transport model of the RADONE computer code that are used in (1) the formulation of the general computational algorithm and (2) the discussion of the stability criteria of the numerical solutions of the governing system of discrete-element equations are

$\overline{C}_{rb,0;i}$ = specified initial bottom concentration of the radionuclide in the bottom layer in element *i*, at specified initial time t_0 [Eq. (5.5b)], radiologic unit/ft^3],

$\overline{C}_{rw,0;i}$ = specified initial water concentration of the radionuclide in the water layer in element *i*, at specified initial time t_0 [Eq. (5.4b)], radiologic unit/ft^3],

$\overline{D}_{mwl;i}$ = mean water level depth (relative to the arbitrarily specified level) in element *i* [Eq. (5.39b), ft],

$\overline{D}_{mwl;i \pm ¼}$ = mean water level depth (relative to the arbitrarily specified level) in the upstream half-element $i - ¼$ or in the downstream half-element $i + ¼$ [Eq. (5.39a), ft],

$[\overline{F}(\overline{G}_x)]_{i-¼}$ = right-hand-side solution function of the discrete-element equations for channel flow rate in the upstream half-element $i - ¼$ [Eq. (5.2a), ft^3/h^2],

$[\overline{F}(\overline{G}_x)]_{i+¼}$ = right-hand-side solution function of the discrete-element equations for channel flow rate in the downstream half-element $i + ¼$ [Eq. (5.3a), ft^3/h^2],

$[\overline{F}(\overline{H})]_i$ = right-hand-side solution function of the discrete-element equations for water surface elevation in element *i* [Eq. (5.1a), ft/h],

$[\overline{F}_{CNV}(\overline{G}_x)]_{i-¼}$ = the part representing convective momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) of the right-hand-side solution function of the discrete-element equation for channel flow rate in the upstream half-element $i - ¼$ [Eqs. (5.2a) and (5.11), ft^3/h^2],

$[\overline{F}_{CNV}(\overline{G}_x)]_{i+\frac{1}{4}}$ = the part representing convective momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) of the right-hand-side solution function of the discrete-element equations for channel flow rate in the downstream half-element $i + \frac{1}{4}$ [Eqs. (5.2a) and (5.17), ft^3/h^2],

$[\overline{F}_{CNV}(\overline{H})]_i$ = the part representing convective water mass transport (along the curvilinear longitudinal x-axis of the main flow channel) of the right-hand-side solution function of the discrete-element equation for water surface elevation in element i [Eqs. (5.1a) and (5.6), ft/h],

$[\overline{F}_{GRD}(\overline{G}_x)]_{i-\frac{1}{4}}$ = the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) associated with groundwater seepage flow into or out of the main flow channel of the right-hand-side solution function of the discrete-element equation for channel flow rate in the upstream half-element $i - \frac{1}{4}$ [Eqs. (5.2a) and (5.13), ft^3/h^2],

$[\overline{F}_{GRD}(\overline{G}_x)]_{i+\frac{1}{4}}$ = the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) associated with groundwater seepage flow into or out of the main flow channel of the right-hand-side solution function of the discrete-element equation for channel flow rate in the downstream half-element $i + \frac{1}{4}$ [Eqs. (5.3a) and (5.19), ft^3/h^2],

$[\overline{F}_{GRD}(\overline{H})]_i$ = the part representing water mass transport associated with groundwater seepage flow into or out of the main flow channel of the right-hand-side solution function of the discrete-element equation for water surface elevation in element i [Eqs. (5.1a) and (5.7), ft/h],

$[\overline{F}_{PLT}(\overline{G}_x)]_{i-\frac{1}{4}}$ = the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) associated with power plant operational conditions along the main flow channel that control intake and discharge flows into and/or out of the main flow channel of the right-hand-side solution function of the discrete-element equation for channel flow rate in the upstream half-element $i - \frac{1}{4}$ [Eqs. (5.2a) and (5.16), ft^3/h^2],

$[\overline{F}_{PLT}(\overline{G}_x)]_{i+\frac{1}{4}}$ = the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) associated with power plant operational conditions along the main flow channel that control intake and discharge flows into and/or out of the main flow channel of the right-hand-side solution function of the discrete-element equation for channel flow rate in the downstream half-element $i + \frac{1}{4}$ [Eqs. (5.3a) and (5.22), ft^3/h^2],

$[\overline{F}_{PLT}(\overline{H})]_i$ = the part representing water mass transport associated with power plant operational conditions along the main flow channel that control intake and discharge flows into and/or out of the main flow channel of the right-hand-side solution function of the discrete-element equation for water surface elevation in element i [Eqs. (5.1a) and (5.10), ft/h],

$(Fr)_{cr}$ = critical Froude number in the main flow channel [Eq. (5.55)],

$[\overline{F}_{SRF}(\overline{G}_x)]_{i-\frac{1}{4}}$ = the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) at the water surface into or out of the main flow channel, which also includes the momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) associated with drainage flow into the main flow channel of the right-hand-side solution function of the discrete-element equation for channel flow rate in the upstream half-element $i - \frac{1}{4}$ [Eqs. (5.2a) and (5.14), ft^3/h^2],

$[\overline{F}_{SRF}(\overline{G}_x)]_{i+\frac{1}{4}}$ = the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) at the water surface into or out of the main flow channel, which also includes the momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) associated with drainage flow into the main flow channel of the right-hand-side solution function of the discrete-element equation for channel flow rate in the downstream half-element $i - \frac{1}{4}$ [Eqs. (5.3a) and (5.20), $\mathrm{ft}^3/\mathrm{h}^2$],

$[\overline{F}_{SRF}(\overline{H})]_i$ = the part representing water mass transport at the water surface into the main flow channel, which also includes the water mass transport associated with the drainage flow into the main flow channel, of the right-hand-side solution function of the discrete-element equation for water surface elevation in element i [Eqs. (5.1a) and (5.8), ft/h],

$[\overline{F}_{SRM}(\overline{G}_x)]_{i-\frac{1}{4}}$ = the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel), associated with stream or tributary flows into or out of the main flow channel, of the right-hand-side solution function of the discrete-element equation for channel flow rate in the upstream half-element $i - \frac{1}{4}$ [Eqs. (5.2a) and (5.15), $\mathrm{ft}^3/\mathrm{h}^2$],

$[\overline{F}_{SRM}(\overline{G}_x)]_{i+\frac{1}{4}}$ = the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel), associated with stream or tributary flows into or out of the main flow channel, of the right-hand-side solution function of the discrete-element equation for channel flow rate in the downstream half-element $i + \frac{1}{4}$ [Eqs. (5.3a) and (5.21), $\mathrm{ft}^3/\mathrm{h}^2$],

$[\overline{F}_{SRM}(\overline{H})]_i$ = the part representing water mass transport associated with stream or tributary flows into or out of the main flow channel of the right-hand-side solution function of the discrete-element equation for water surface elevation in element i [Eqs. (5.1a) and (5.9), ft/h],

$[\overline{F}_{TRB}(\overline{G}_x)]_{i-\frac{1}{4}}$ = the part representing nonconvective momentum transport (convection-defect momentum transport along the curvilinear longitudinal x-axis of the main flow channel) of the right-hand-side solution function of the discrete-element equation for channel flow rate in the upstream half-element $i - \frac{1}{4}$ [Eqs. (5.2a) and (5.12), $\mathrm{ft}^3/\mathrm{h}^2$],

$[\overline{F}_{TRB}(\overline{G}_x)]_{i+\frac{1}{4}}$ = the part representing nonconvective momentum transport (convection-defect momentum transport along the curvilinear longitudinal x-axis of the main flow channel) of the right-hand-side solution function of the discrete-element equation for channel flow rate in the downstream half-element $i + \frac{1}{4}$ [Eqs. (5.3a) and (5.18), $\mathrm{ft}^3/\mathrm{h}^2$],

$\overline{G}_{x,0;i-\frac{1}{4}}$ = specified initial channel flow rate in the upstream half-element $i - \frac{1}{4}$ [Eq. (5.2b), ft^3/h],

$\overline{G}_{x,0;i+\frac{1}{4}}$ = specified initial channel flow rate in the downstream half-element $i + \frac{1}{4}$ [Eq. (5.3b), ft/h],

$\overline{H}_{0;i}$ = specified initial water surface elevation in element i [Eq. (5.1b), ft],

$\overline{H}_{mwl;i}$ = water surface elevation difference (relative to the mean water level) in element i [Eq. (5.39b), ft],

$\overline{H}_{mwl;i\pm\frac{1}{4}}$ = water surface elevation difference (relative to the mean water level in the upstream half-element $i - \frac{1}{4}$ or in the downstream half-element $i + \frac{1}{4}$ [Eq. (5.39a), ft],

$(\overline{R}_{x;i,i\pm1})_{\max}$ = maximum value of the ratio of the curvilinear lengths of adjacent elements [Eqs. (5.37) and (5.38),

$\overline{R}(\Delta t)$ = ratio of the maximum allowable time steps associated with the numerical solution of (1) hydrodynamic conditions and (2) radionuclide concentration conditions [Eqs. (5.53a) and (5.53b)],

t_0 = specified initial time associated with the time of calculations (h),

$V_{rw,bot}$ = bottom-settling (deposition) velocity (along the geophysical vertical z-axis) associated with the bottom-settling (deposition) radionuclide transport rate out of the water layer into the bottom layer in the main flow channel [Eq. (5.44), ft/h],

$V_{rw,bot;i}$ = bottom-settling (deposition) velocity (along the geophysical vertical z-axis) associated with the bottom-settling (deposition) radionuclide transport rate out of the water layer into the bottom layer in element i [Eqs. (5.45), ft/h],

$(|\overline{V}_{x;i}|)_{\max}$ = maximum absolute value of channel flow velocity in the main flow channel in the element i [Eqs. (5.37) and (5.43), ft/h],

$\overline{v}_{\omega;i}$ = surface wave speed (celerity) associated with the surface wave phenomenon in element i [Eq. (5.40b), ft/h],

$\overline{v}_{\omega;i \pm 1/4}$ = surface wave speed (celerity) associated with the surface wave phenomenon in the upstream half-element $i - 1/4$ or in the downstream half-element $i + 1/4$ [Eqs. (5.39a) and (5.40b), ft/h],

$(\overline{v}_{\omega;i})_{\max}$ = maximum value of surface wave speed (celerity) in the main flow channel associated with the surface wave phenomenon in element i [Eqs. (5.37) and (5.40a), ft/h],

$(\overline{v}_{\omega;i \pm 1/4})_{\max}$ = maximum value of surface wave speed (celerity) in the main flow channel associated with the surface wave phenomenon in the upstream half-element $i - 1/4$ or in the downstream half-element $i + 1/4$ [Eq. (5.40a), ft/h],

Δt = time step of numerical integration (h),

$\Delta t\{\overline{C}_{rw}\}_{bot}$ = maximum allowable time step for the numerical solution of water concentration of the radionuclide in the water layer based on the bottom transport effect criterion [Eq. (5.45), h],

$\Delta t\{\overline{C}_{rw}\}_{CNV}$ = maximum allowable time step for the numerical solution of water concentration of the radionuclide in the water layer based on the convective transport effect criterion [Eq. (5.41), h],

$\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_{nuc}$ = maximum allowable time step for the numerical solution of radionuclide concentration conditions based on the nuclear decay effect criterion [Eq. (5.47), h],

$\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_1$ = maximum allowable time step for the numerical solution of radionuclide concentration conditions based on the primary stability criterion for radionuclide concentration conditions (convective effect criterion) [Eq. (5.50), h],

$\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_{2,bot}$ = maximum allowable time step for the numerical solution of radionuclide concentration conditions based on the secondary stability criterion for radionuclide concentration conditions (bottom transport effect criterion) [Eq. (5.51), h],

$\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_{2,nuc}$ = maximum allowable time step for the numerical solution of radionuclide concentration conditions based on the secondary stability criterion for radionuclide concentration conditions (nuclear decay effect criterion) [Eq. (5.52), h],

$\Delta t\{\overline{H},\overline{G}_x\}$ = maximum allowable time step for the numerical solution of hydrodynamic conditions based on necessary and sufficient stability criteria [Eq. (5.37), h],

$\Delta t\{\overline{H},\overline{G}_x\}_1$ = maximum allowable time step for the numerical solution of hydrodynamic conditions based on primary stability criterion for hydrodynamic conditions [Eqs. (5.37) and (5.49), h],

$(\Delta x_i)_{\min}$ = minimum value of the curvilinear length of the discrete-element i (along the curvilinear longitudinal x-axis of the main flow channel), representing the curvilinear length of the smallest channel segment (ft),

5.2 COMPUTATIONAL PROCEDURE OF NUMERICAL SOLUTION OF GOVERNING SYSTEM OF DISCRETE-ELEMENT EQUATIONS

The governing discrete-element computational procedure for the principal solution variables consists of (1) the discrete-element equation for water surface elevation $\overline{H}_i$ in element i [Eq. (2.1)], (2) the discrete-element equations for channel flow rate $\overline{G}_{x;i-\frac{1}{4}}$ in upstream half-element $i - \frac{1}{4}$ [Eq. (2.2)], and $\overline{G}_{x;i+\frac{1}{4}}$ in downstream half-element $i + \frac{1}{4}$ [Eq. (2.3)], (3) the discrete-element equation for water concentration of the radionuclide in the water layer in element i [Eq. (2.4)], and (4) the discrete-element equation for bottom concentration of the radionuclide in the bottom layer in element i [Eq. (2.16)]. The discrete-element computational system represents an initial value problem of $5N$ number of first-order, moderately coupled, quasi-linear ordinary differential equations, subject to $5N$ number of associated initial conditions specified at any arbitrarily specified initial time t_0.

1. Computational subsystem of discrete-element equations for water surface elevation H_i in element i [Eq. (2.1)] can be represented as

$$\frac{\partial \overline{H}_i}{\partial t}(t) = [\overline{F}(\overline{H})]_i = [\overline{F}_{CNV}(\overline{H})]_i + [\overline{F}_{GRD}(\overline{H})]_i$$

$$+ [\overline{F}_{SRF}(\overline{H})] + [\overline{F}_{SRM}(\overline{H})]_i + [\overline{F}_{PLT}(\overline{H})]_i \ , \qquad (5.1a)$$

with the associated set of initial conditions as

$$\overline{H}_i(t_0) = \overline{H}_{0;i} \ , \ \text{specified at} \ \ t = t_0 \ . \qquad (5.1b)$$

2. Computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i-\frac{1}{4}}$ in upstream half-element $i - \frac{1}{4}$ [Eq. (2.2)] can be represented as

$$\frac{\partial \overline{G}_{x;i-\frac{1}{4}}}{\partial t}(t) = [\overline{F}(\overline{G}_x)]_{i-\frac{1}{4}} = [\overline{F}_{CNV}(\overline{G}_x)]_{i-\frac{1}{4}} + [\overline{F}_{TRB}(\overline{G}_x)]_{i-\frac{1}{4}}$$

$$+ [\overline{F}_{GRD}(\overline{G}_x)]_{i-\frac{1}{4}} + [\overline{F}_{SRF}(\overline{G}_x)]_{i-\frac{1}{4}} + [\overline{F}_{SRM}(\overline{G}_x)]_{i-\frac{1}{4}} + [\overline{F}_{PLT}(\overline{G}_x)]_{i-\frac{1}{4}} \ , \qquad (5.2a)$$

with the associated set of initial conditions as

$$\overline{G}_{x;i-\frac{1}{4}}(t_0) = \overline{G}_{x,0;i-\frac{1}{4}} \ , \ \text{specified at} \ \ t = t_0 \ . \qquad (5.2b)$$

3. Computational subsystems of discrete-element equations for channel flow rate $\overline{G}_{x;i+\frac{1}{4}}$ in downstream half-element $i + \frac{1}{4}$ [Eq. (2.3)] can be represented as

$$\frac{\partial \overline{G}_{x;i+\frac{1}{4}}}{\partial t}(t) = [\overline{F}(\overline{G}_x)]_{i+\frac{1}{4}} = [\overline{F}_{CNV}(\overline{G}_x)]_{i+\frac{1}{4}} + [\overline{F}_{TRB}(\overline{G}_x)]_{i+\frac{1}{4}}$$

$$+ [\overline{F}_{GRD}(\overline{G}_x)]_{i+\frac{1}{4}} + [\overline{F}_{SRF}(\overline{G}_x)]_{i+\frac{1}{4}} + [\overline{F}_{SRM}(\overline{G}_x)]_{i+\frac{1}{4}} + [\overline{F}_{PLT}(\overline{G}_x)]_{i+\frac{1}{4}} \ , \qquad (5.3a)$$

with the associated set of initial conditions as

$$\overline{G}_{x;i+\frac{1}{2}}(t_0) = \overline{G}_{x,0;i+\frac{1}{2}} \ , \ \text{specified at} \ \ t = t_0 \qquad (5.3b)$$

4. Computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4) and (2.13)] can be represented as

$$\frac{\partial \overline{C}_{rw;i}}{\partial t}(t) = [\overline{F}_{WL}(\overline{C}_{rw})]_i = [\overline{F}_{CNV}(\overline{C}_{rw})]_i + [\overline{F}_{TRB}(\overline{C}_{rw})]_i + [\overline{F}_{GRD}(\overline{C}_{rw})]_i$$

$$+ [\overline{F}_{BOT}(\overline{C}_{rw})]_i + [\overline{F}_{SRF}(\overline{C}_{rw})]_i + [\overline{F}_{SRM}(\overline{C}_{rw})]_i + [\overline{F}_{PLT}(\overline{C}_{rw})]_i + [\overline{F}_{RAD}(\overline{C}_{rw})]_i \ , \qquad (5.4a)$$

with the associated set of initial conditions as

$$\overline{C}_{rw;i}(t_0) = \overline{C}_{rw,0;i} \ , \ \text{specified at} \ \ t = t_0 \ . \qquad (5.4b)$$

5. Computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16) and (2.22)] can be represented as

$$\frac{\partial \overline{C}_{rb;i}}{\partial t}(t) = [\overline{F}_{BL}(\overline{C}_{rb})]_i = [\overline{F}_{GRD}(\overline{C}_{rb})]_i + [\overline{F}_{BOT}(\overline{C}_{rb})]_i$$

$$+ [\overline{F}_{SRM}(\overline{C}_{rb})]_i + [\overline{F}_{PLT}(\overline{C}_{rb})]_i + [\overline{F}_{RAD}(\overline{C}_{rb})]_i \ , \qquad (5.5a)$$

with the associated set of initial conditions as

$$\overline{C}_{rb;i}(t_0) = \overline{C}_{rb,0;i} \ , \ \text{specified at} \ \ t = t_0 \ . \qquad (5.5b)$$

The set of right-hand-side solution functions represents the set of slopes (in the time-solution space) of the set of principal solution variables, consisting of

1. $[\overline{F}(\overline{H})]_i$ for water surface elevation $\overline{H}_i$ in element i [Eq. (5.1a)],
2. $[\overline{F}(\overline{G}_x)]_{i-\frac{1}{2}}$ for channel flow rate $\overline{G}_{x;i-\frac{1}{2}}$ in upstream half-element $i - \frac{1}{2}$ [Eq. (5.2a)],
3. $[\overline{F}(\overline{G}_x)]_{i+\frac{1}{2}}$ for channel flow rate $\overline{G}_{x;i+\frac{1}{2}}$ in downstream half-element $i + \frac{1}{2}$ [Eq. (5.3a)],
4. $[\overline{F}_{WL}(\overline{C}_{rw})]_i$ for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eq. (5.4a)], and
5. $[\overline{F}_{BL}(\overline{C}_{rb})]_i$ for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eq. (5.5a)].

The formulations of three sets of right-hand-side solution functions consisting of (1) the set of right-hand-side solution functions $[\overline{F}(\overline{H})]_i$ for water surface elevation $\overline{H}_i$ in element i [Eq. (5.1a)], (2) the set of right-hand-side solution functions $[\overline{F}(\overline{G}_x)]_{i-\frac{1}{2}}$ for channel flow rate $\overline{G}_{x;i-\frac{1}{2}}$ in upstream half-element $i - \frac{1}{2}$ [Eq. (5.2a)], and (3) the set of right-hand-side solution functions $[\overline{F}(\overline{G}_x)]_{i+\frac{1}{2}}$ for channel flow rate $\overline{G}_{x;i+\frac{1}{2}}$ in downstream half-element $i + \frac{1}{2}$ [Eq. (5.3a)] are discussed in detail in the development of the hydrodynamic submodel of the fast-transient, one-dimensional, discrete-element model and its associated ESTONE computer code [Eraslan (1983)] for simulating flow, water temperature, and salinity conditions in controlled rivers and tidal estuaries.

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The right-hand-side solution function $[\overline{F}(\overline{H})]_i$ for water surface elevation $\overline{H}_i$ in element i [Eq. (5.10)] consists of the sum of the following five parts [Eq. (2.1)]:

1. the part representing convective water mass transport (along the curvilinear longitudinal x-axis of the main flow channel):

$$[\overline{F}_{CNV}(\overline{H})]_i = \frac{1}{\Delta x_i \overline{B}_{srf;i}} (\overline{G}_{x;i-\frac{1}{2}} - \overline{G}_{x;i+\frac{1}{2}}) \;; \tag{5.6}$$

2. the part representing water mass transport associated with groundwater seepage flow into or out of the main flow channel:

$$[\overline{F}_{GRD}(\overline{H})]_i = \frac{1}{\Delta x_i \overline{B}_{srf;i}} \overline{G}_{grd;i} \;; \tag{5.7}$$

3. the part representing water mass transport at the water surface into the main flow channel, which also includes the water mass transport associated with drainage flow into the main flow channel:

$$[\overline{F}_{SRF}(\overline{H})]_i = \overline{g}_{rnf} \left(1 + \frac{\overline{A}_{drn;i}}{\Delta x_i \overline{B}_{srf;i}} \right) \;; \tag{5.8}$$

4. the part representing water mass transport associated with stream or tributary flows into or out of the main flow channel:

$$[\overline{F}_{SRM}(\overline{H})]_i = \frac{\delta_{srm,n;i}}{\Delta x_i \overline{B}_{srf;i}} \overline{G}_{srm,n} \;; \tag{5.9}$$

5. the part representing water mass transport associated with power plant operational conditions (along the main flow channel) that control intake and discharge flows into and/or out of the main flow channel:

$$[\overline{F}_{PLT}(\overline{H})]_i = \frac{\delta_{int,m;i}}{\Delta x_i \overline{B}_{srf;i}} \overline{G}_{int,m} + \frac{\delta_{dis,m;i}}{\Delta x_i \overline{B}_{srf;i}} \overline{G}_{dis,m} \tag{5.10}$$

The right-hand-side solution function $[\overline{F}(\overline{G}_x)]_{i-\frac{1}{4}}$ for channel flow rate $\overline{G}_{x;i-\frac{1}{4}}$ in upstream half-element $i-\frac{1}{4}$ [Eq. (5.2a) consists of the sum of the following six parts [Eq. (2.2)]:

1. the part representing convective momentum transport (along the curvilinear longitudinal x-axis of the main flow channel), which also includes, for convenience, the net force effect of the hydrostatic pressure force (along the curvilinear longitudinal x-axis of the main flow channel) and the gravitational body force (along the curvilinear longitudinal x-axis of the main flow channel):

$$[\overline{F}_{CNV}(\overline{G}_x)]_{i-\frac{1}{4}} = \frac{2}{\Delta x_i} (\overline{G}_{x;i-\frac{1}{2}} \overline{V}_{x;i-\frac{1}{2}} - \overline{G}_{x;i} \overline{V}_{x;i})$$

$$\frac{2g_a}{} [\overline{A}_{i-\frac{1}{2}}(\overline{H}_{i-\frac{1}{2}} - \overline{H}_{i-\frac{1}{4}}) - \overline{A}_i(\underset{\Delta x}{\overline{H}_i} - \overline{H}_{i-\frac{1}{4}})] + g_a \overline{A}_{i-\frac{1}{4}} \overline{\Omega}_x \;; \tag{5.11}$$

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2. the part representing nonconvective momentum transport (convection-defect momentum transport along the curvilinear longitudinal *x*-axis of the main flow channel), which also includes bottom drag force (along the curvilinear longitudinal *x*-axis of the main flow channel):

$$[\overline{F}_{TRB}(\overline{G}_x)]_{l-\frac{1}{4}} = \frac{2}{\Delta x_l}(\overline{G}^{*\prime}_{x;l-\frac{1}{2}} - \overline{G}^{*\prime}_{x;l}) + \overline{F}^{\prime}_{x,bot;l-\frac{1}{4}} \;; \tag{5.12}$$

3. the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with groundwater seepage flow into or out of the main flow channel:

$$[\overline{F}_{GRD}(\overline{G}_x)]_{l-\frac{1}{4}} = \frac{1}{\Delta x_l}\overline{G}_{grd;l}\widetilde{V}_{x,grd;l} \;; \tag{5.13}$$

4. the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) at the water surface into or out of the main flow channel, which also includes the momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with drainage flow into the main flow channel:

$$[\overline{F}_{SRF}(\overline{G}_x)]_{l-\frac{1}{4}} = \overline{B}_{srf;l-\frac{1}{4}}\left[\bar{g}_{rnf}\left(\overline{V}_{x,rnf;l} + \frac{\overline{A}_{drn;l}}{\overline{B}_{srf;l-\frac{1}{4}}\Delta x_l}\overline{V}_{x,drn;l}\right) + \tilde{j}^{\prime}_{x,srf;l-\frac{1}{4}}\right] \;; \tag{5.14}$$

5. the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with stream or tributary flows into or out of the main flow channel:

$$[\overline{F}_{SRM}(\overline{G}_x)]_{l-\frac{1}{4}} = \frac{\delta_{srm,n;l}}{\Delta x_l}\overline{G}_{srm,n}\widetilde{V}_{x,srm,n;l} \;; \tag{5.15}$$

6. the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with power plant operational conditions along the main flow channel, which control intake and discharge flows into and/or out of the main flow channel:

$$[\overline{F}_{PLT}(\overline{G}_x)]_{l-\frac{1}{4}} = \frac{\delta_{int,m;l}}{\Delta x_l}\overline{G}_{int,m}\widetilde{V}_{x,int,m;l} + \frac{\delta_{dis,m;l}}{\Delta i_l}\overline{G}_{dis,m}\widetilde{V}_{x,dis,m} \;. \tag{5.16}$$

Similarly, the right-hand-side solution function $[\overline{F}(\overline{G}_x)]_{l+\frac{1}{4}}$ for channel flow rate $\overline{G}_{x;l+\frac{1}{4}}$ in downstream half-element $l + \frac{1}{4}$ [Eq. (5.3a)] consists of the sum of the following six parts [Eq. (2.3)]:

1. the part representing convective momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel), which also includes, for convenience, the net force effect of the hydrostatic pressure force (along the curvilinear longitudinal *x*-axis of the main flow channel) and the gravitational body force (along the curvilinear longitudinal *x*-axis of the main flow channel):

$$[\overline{F}_{CNV}(\overline{G}_x)]_{l+\frac{1}{4}} = \frac{2}{\Delta x_i}(\overline{G}_{x;l}\widetilde{V}_{x;l} - \overline{G}_{x;l+\frac{1}{2}}\widetilde{V}_{x;l+\frac{1}{2}})$$

$$+ \frac{2g_a}{\Delta x_l}[\overline{A}_l(\overline{H}_l - \overline{H}_{l+\frac{1}{4}}) - \overline{A}_{l+\frac{1}{2}}(\overline{H}_{l+\frac{1}{2}} - \overline{H}_{l+\frac{1}{4}})] + g_a\overline{A}_{l+\frac{1}{4}}\overline{\Omega}_x \;; \tag{5.17}$$

2. the part representing nonconvective momentum transport (convection-defect momentum transport along the curvilinear longitudinal x-axis of the main flow channel), which also includes bottom drag force (along the curvilinear longitudinal x-axis of the main flow channel):

$$[\overline{F}_{TRB}(\overline{G}_x)]_{l+1/2} = \frac{2}{\Delta x_l}(\overline{G}^{\bullet\prime}_{x;l} - \overline{G}^{\bullet\prime}_{x;l+1/2}) + \overline{F}_{x,bot;l+1/2} \;; \tag{5.18}$$

3. the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) associated with groundwater seepage flow into or out of the main flow channel:

$$[\overline{F}_{GRD}(\overline{G}_x)]_{l+1/2} = \frac{1}{\Delta x_l}\overline{G}_{grd;l}\overline{V}_{x,grd;l} \;; \tag{5.19}$$

4. the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) at the water surface into or out of the main flow channel, which also includes the momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) associated with drainage flow into the main flow channel:

$$[\overline{F}_{SRF}(\overline{G}_x)]_{l+1/2} = \overline{B}_{srf;l+1/2}\left[\overline{g}_{rnf}\left(\overline{V}_{x,rnf;l} + \frac{\overline{A}_{drn;l}}{\overline{B}_{srf;l+1/2}\Delta x_l}\overline{V}_{x,drn;l}\right) + \overline{J}'_{x,srf;l+1/2}\right] \;; \tag{5.20}$$

5. the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) associated with stream or tributary flows into or out of the main flow channel:

$$[\overline{F}_{SRM}(\overline{G}_x)]_{l+1/2} = \frac{\delta_{srm,n;l}}{\Delta x_l}\overline{G}_{srm,n}\overline{V}_{x,srm,n;l} \;; \tag{5.21}$$

6. the part representing momentum transport (along the curvilinear longitudinal x-axis of the main flow channel) associated with power plant operational conditions along the main flow channel that control intake and discharge flows into and/or out of the main flow channel:

$$[\overline{F}_{PLT}(\overline{G}_x)]_{l+1/2} = \frac{\delta_{int,m;l}}{\Delta x_l}\overline{G}_{int,m}\overline{V}_{x,int,m;l} + \frac{\delta_{dis,m;l}}{\Delta x_l}\overline{G}_{dis,m}\overline{V}_{x,dis,m} \;. \tag{5.22}$$

The formulations of the remaining two sets of right-hand-side solution functions, consisting of (1) the set of right-hand-side solution functions $[\overline{F}_{WL}(\overline{C}_{rw})]_l$ for water concentration of the radionuclide in the water layer $\overline{C}_{rw;l}$ in element l [Eq. (5.4a)] and (2) the set of right-hand-side solution functions $[\overline{F}_{BL}(\overline{C}_{rb})]_l$ for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;l}$ in element l [Eq. (5.5a)], are already presented in Sects. 2.3.3 and 2.3.4, which contain the development of the submodel for the transport of the radionuclide in the main flow channel of a controlled river or a tidal estuary.

The right-hand-side solution function $[\overline{F}_{WL}(\overline{C}_{rw})]_l$ for water concentration of the radionuclide in the water layer $\overline{C}_{rw;l}$ in element l [Eq. (5.4a)] consists of the sum of the following eight parts:

1. the part representing convective radionuclide transport (along the curvilinear longitudinal x-axis of the main flow channel):

   $[\overline{F}_{CNV}(\overline{C}_{rw})]_l$ is formulated in Eq. (2.5);

2. the part representing nonconvective radionuclide transport (convection-defect radionuclide transport, molecular radionuclide transport, and eddy-turbulent radionuclide transport, along the curvilinear longitudinal x-axis of the main flow channel):

   $[\overline{F}_{TRB}(\overline{C}_{rw})]_i$ is formulated in Eq. (2.6):

3. the part representing convective radionuclide transport associated with the groundwater seepage flow into or out of the water layer in the main flow channel:

   $[\overline{F}_{GRD}(\overline{C}_{rw})]_i$ is formulated in Eq. (2.7);

4. the part representing bottom radionuclide transport at the bottom of the water layer, associated with all the phenomena that can contribute to the transport of the radionuclide between the water layer and the bottom layer:

   $[\overline{F}_{BOT}(\overline{C}_{rw})]_i$ is formulated in Eq. (2.8);

5. the part representing radionuclide transport associated with the rainfall in the geographic (climatological) region of the main flow channel, including the direct radionuclide transport into the main flow channel, resulting from the rainfall on the water surface and the indirect radionuclide transport into the main flow channel, resulting from the drainage inflow, controlled by the rainfall and the radionuclide concentration conditions on the drainage areas in the geographic region:

   $[\overline{F}_{SRF}(\overline{C}_{rw})]_i$ is formulated in Eq. (2.9);

6. the part representing the convective radionuclide transport, associated with the flow of stream or tributary n, into or out of the water layer in the main flow channel:

   $[\overline{F}_{SRM}(\overline{C}_{rw})]_i$ is formulated in Eq. (2.10);

7. the part representing the net convective radionuclide transport, associated with the intake flow and the discharge flow of plant m, into and/or out of the water layer in the main flow channel:

   $[\overline{F}_{PLT}(\overline{C}_{rw})]_i$ is formulated in Eq. (2.11); and

8. the part representing the radiological decay of the radionuclide in the water layer in the main flow channel:

   $[\overline{F}_{RAD}(\overline{C}_{rw})]_i$ is formulated in Eq. (2.12).

Similarly, the right-hand-side solution function $[\overline{F}_{BL}(\overline{C}_{rb})]_i$ for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eq. (5.5a)] consists of the sum of the following five parts:

1. the part representing convective radionuclide transport associated with the groundwater seepage flow into or out of the water layer in the main flow channel:

   $[\overline{F}_{GRD}(\overline{C}_{rb})]_i$ is formulated in Eq. (2.17);

2. the part representing bottom radionuclide transport at the top of the bottom layer, associated with all the phenomena that can contribute to the transport of the radionuclide between the water layer and the bottom layer:

   $[\overline{F}_{BOT}(\overline{C}_{rb})]_i$ is formulated in Eq. (2.18);

3. the part representing the convective radionuclide transport, associated with the flow of stream or tributary *n*, into or out of the bottom layer in the main flow channel:

   $[\overline{F}_{SRM}(\overline{C}_{rb})]_i$ is formulated in Eq. (2.19);

4. the part representing the net convective radionuclide transport, associated with the intake flow and/or the discharge flow of plant *m*, into and/or out of the bottom layer in the main flow channel:

   $[\overline{F}_{PLT}(\overline{C}_{rb})]_i$ is formulated in Eq. (2.20); and

5. the part representing the radiological decay of the radionuclide in the bottom layer in the main flow channel:

   $[\overline{F}_{RAD}(\overline{C}_{rb})]_i$ is formulated in Eq. (2.21).

According to the fundamental concept of UTA [Eraslan et al. (1977), Eraslan and Witten (1984)], the standard computational procedure of all transient, one-dimensional discrete-element transport models [e.g., Eraslan (1983); Hetrick, Eraslan, and Patterson (1978); Fischer et al. (1984)] calculates each set of the eight phenomenological parts of the 5*N* right-hand-side solution functions [Eqs. (5.1a), (5.2a), (5.3a), (5.4a), and (5.5a)] separately by one of the eight major subroutines of the RADTWO computer code. These major subroutines are as follows:

1. CONVEC for calculating the phenomenological parts of the 4*N* number of right-hand-side solution functions which represent the net convective transport effects, consisting of (a) $[\overline{F}_{CNV}(\overline{H})]_i$ in all *N* elements [Eq. (5.6)], (b) $[\overline{F}_{CNV}(\overline{G}_x)]_{i-¼}$ in all *N* upstream half-elements [Eq. (5.11)], (c) $[\overline{F}_{CNV}(\overline{G}_x)]_{i+¼}$ in all *N* downstream half-elements [Eq. (5.12)], and (d) $[\overline{F}_{CNV}(\overline{C}_{rw})]_i$ in all *N* elements [Eq. (2.5)],
2. TURBUL for calculating the phenomenological parts of the 3*N* number of right-hand-side solution functions which represent the net nonconvective transport (convection-defect transport and eddy-turbulent transport) effects, consisting of (a) $[\overline{F}_{TRB}(\overline{G}_x)]_{i-¼}$ in all *N* upstream half-elements [Eq. (5.12), (b) $[\overline{F}_{TRB}(\overline{G}_x)]_{i+¼}$ in all *N* downstream half-elements [Eq. (5.18)], and (c) $[\overline{F}_{TRB}(\overline{C}_{rw})]_i$ in all *N* elements [Eq. (2.6)],
3. GROUND for calculating the phenomenological parts of the 5*N* number of right-hand-side solution functions which represent the net convective transport effects associated with the groundwater seepage flow conditions, consisting of (a) $[\overline{F}_{GRD}(\overline{H})]_i$ in all *N* elements [Eq. (5.6)], (b) $[\overline{F}_{GRD}(\overline{G}_x)]_{i-¼}$ in all *N* upstream half-elements [Eq. (5.13)], (c) $[\overline{F}_{GRD}(\overline{G}_x)]_{i+¼}$ in all *N* downstream half-elements [Eq. (5.19)], (d) $[\overline{F}_{GRD}(\overline{C}_{rw})]_i$ in all *N* elements [Eq. (2.7)], and (e) $[\overline{F}_{GRD}(\overline{C}_{rb})]_i$ in all *N* elements [Eq. (2.17)],
4. BOTTOM for calculating the phenomenological parts of the 2*N* number of right-hand-side solution functions which represent the net radionuclide transport effects between the water layer and the bottom layer, consisting of (a) $[\overline{F}_{BOT}(\overline{C}_{rw})]_i$ in all *N* elements [Eq. 2.8)] and (b) $[\overline{F}_{BOT}(\overline{C}_{rb})]_i$ in all *N* elements [Eq. (2.18)],
5. SURFAC for calculating the phenomenological parts of the 4*N* number of right-hand-side solution functions which represent the net convective transport effects at the water surface, consisting of (a) $[\overline{F}_{SRF}(\overline{H})]_i$ in all *N* elements [Eq. (5.8)], (b) $[\overline{F}_{SRF}(\overline{G}_x)]_{i-¼}$ in all *N* upstream half-elements [Eq. (5.14)], (c) $[\overline{F}_{SRF}(\overline{G}_x)]_{i+¼}$ in all *N* downstream half-elements [Eq. (5.20)], and (d) $[\overline{F}_{SRF}(\overline{C}_{rw})]_i$ in all *N* elements [Eq. (2.9)],

6. STREAM for calculating the phenomenological parts of the $5N$ number of right-hand-side solution functions which represent the net convective transport effects associated with the stream and/or tributary flow conditions, consisting of (a) $[\overline{F}_{SRM}(\overline{H})]_i$ in all N elements [Eq. (5.9)], (b) $[\overline{F}_{SRM}(\overline{G}_x)]_{i-¼}$ in all N upstream half-elements [Eq. (5.15)], (c) $[\overline{F}_{SRM}(\overline{G}_x)]_{i+¼}$ in all N downstream half-elements [Eq. (5.21), (d) $[\overline{F}_{SRM}(\overline{C}_{rw})]_i$ in all N elements [Eq. (2.10)], and (e) $[\overline{F}_{SRM}(\overline{C}_{rb})]_i$ in all N elements [Eq. (2.19)],
7. PLANTS for calculating the phenomenological parts of the $5N$ number of right-hand-side solution functions which represent the net convective transport effects associated with the intake flow conditions and discharge flow conditions of the operational plants, consisting of (a) $[\overline{F}_{PLT}(\overline{H})]_i$ in all N elements [Eq. (5.10)], (b) $[\overline{F}_{PLT}(\overline{G}_x)]_{i-¼}$ in all N upstream half-elements [Eq. (5.16)], (c) $[\overline{F}_{PLT}(\overline{G}_x)]_{i+¼}$ in all N downstream half-elements [Eq. (5.22)], (d) $[\overline{F}_{PLT}(\overline{C}_{rw})]_i$ in all N elements [Eq. (2.11)], and (e) $[\overline{F}_{PLT}(\overline{C}_{rb})]_i$ in all N elements [Eq. (2.20)], and
8. RADIOR for calculating the phenomenological parts of the $2N$ number of right-hand-side solution functions which represent the radiologic decay effects, consisting of (a) $[\overline{F}_{RAD}(\overline{C}_{rw})]_i$ in all N elements [Eq. (2.12)], and (b) $[\overline{F}_{RAD}(\overline{C}_{rb})]_i$ in all N elements [Eq. (2.21)].

The solution of the governing computational system of discrete-element equations, consisting of (1) computational subsystem of discrete-element equations for water surface elevation $\overline{H}_i$ in N elements [Eqs. (5.1a) and (5.1b)], (2) computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i-¼}$ in N upstream half-elements [Eqs. (5.2a) and (5.2b)], (3) computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i+¼}$ in N downstream half-elements [Eqs. (5.3a) and (5.3b)], (4) computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in N elements [Eqs. (5.4a) and (5.4b)], and (5) computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in N elements [Eqs. (5.5a) and (5.5b)], which represent collectively a first-order, initial value problem for the set of $5N$ number of solution variables, is based on the application of a fourth-order Runge-Kutta-Gill numerical integration technique [e.g., Conte and DeBoor (1972)] which is formulated as the major solution subroutine SOLVER. The complete numerical solution procedure of the RADONE computer code is controlled by the major solution subroutine SOLVER, which sequentially utilizes all eight major subroutines associated with the calculations of the eight phenomenological parts that collectively constitute the $5N$ number of right-hand-side solution functions [Eqs. (5.1a), (5.2a), (5.3a), (5.4a), and (5.5a)]. The computational control of the major solution subroutine SOLVER uses a sequential call method based on a successive updating scheme of the values of $5N$ number of right-hand-side solution functions, consisting of (1) $[\overline{F}(\overline{H})]_i$ of the discrete-element equation for water surface elevation $\overline{H}_i$ in all N elements [Eq. (5.1a)], (2) $[\overline{F}(\overline{G}_x)]_{i-¼}$ of the discrete-element equation for channel flow rate $\overline{G}_{x;i-¼}$ in all N upstream half-elements [Eq. (5.2a)], (3) $[\overline{F}(\overline{G}_x)]_{i+¼}$ of the discrete-element equation for channel flow rate $\overline{G}_{x;i+¼}$ in all N downstream half-elements, (4) $[\overline{F}_{WL}(\overline{C}_{rw})]_i$ of the discrete-element equation for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in all N elements, and (5) $[\overline{F}_{BL}(\overline{C}_{rb})]_i$ of the discrete-element equation for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in all N elements. The sequential computational procedure of the RADONE computer code calls successively from the major solution subroutine SOLVER the eight major subroutines (CONVEC, TURBUL, GROUND, BOTTOM, SURFAC, STREAM, PLANTS, and RADIOR), which successively calculate the contributions of at most eight phenomenological effects that control the variations of the conditions associated with the five principal solution variables in N number of elements and $2N$ number of half-elements, according to the mathematical formulation of the fast-transient, one-dimensional, two-layer discrete-element radionuclide transport model.

1. CONVEC completes the computational sequence of successive updating scheme for

$$[\bar{F}(\bar{H})]_i = [\bar{F}_{CNV}(\bar{H})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ , \tag{5.23a}$$

$$[\bar{F}(\bar{G}_x)]_{i-\frac{1}{4}} = [\bar{F}_{CNV}(\bar{G}_x)]_{i-\frac{1}{4}} \ , \ \text{for all upstream half-elements } (i - \tfrac{1}{4}) = 1, \ldots, N \ , \tag{5.23b}$$

$$[\bar{F}(\bar{G}_x)]_{i+\frac{1}{4}} = [\bar{F}_{CNV}(\bar{G}_x)]_{i+\frac{1}{4}} \ , \ \text{for all downstream half-elements } (i + \tfrac{1}{4}) = 1, \ldots, N \ , \tag{5.23c}$$

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{CNV}(\bar{C}_{rw})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ . \tag{5.23d}$$

2. TURBUL completes the computational sequence of successive updating scheme for

$$[\bar{F}(\bar{G}_x)]_{i-\frac{1}{4}} = [\bar{F}_{TRB}(\bar{G}_x)]_{i-\frac{1}{4}} \ , \ \text{for all upstream half-elements } (i - \tfrac{1}{4}) = 1, \ldots, N \ , \tag{5.24a}$$

$$[\bar{F}(\bar{G}_x)]_{i+\frac{1}{4}} = [\bar{F}_{TRB}(\bar{G}_x)]_{i+\frac{1}{4}} \ , \ \text{for all downstream half-elements } (i + \tfrac{1}{4}) = 1, \ldots, N \ , \tag{5.24b}$$

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{TRB}(\bar{C}_{rw})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ . \tag{5.24c}$$

3. GROUND completes the computational sequence of successive updating scheme for

$$[\bar{F}(\bar{H})]_i = [\bar{F}_{GRD}(\bar{H})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ , \tag{5.25a}$$

$$[\bar{F}(\bar{G}_x)]_{i-\frac{1}{4}} = [\bar{F}_{GRD}(\bar{G}_x)]_{i-\frac{1}{4}} \ , \ \text{for all upstream half-elements } (i - \tfrac{1}{4}) = 1, \ldots, N \ , \tag{5.25b}$$

$$[\bar{F}(\bar{G}_x)]_{i+\frac{1}{4}} = [\bar{F}_{GRD}(\bar{G}_x)]_{i+\frac{1}{4}} \ , \ \text{for all downstream half-elements } (i + \tfrac{1}{4}) = 1, \ldots, N \ , \tag{5.25c}$$

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{GRD}(\bar{C}_{rw})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ , \tag{5.25d}$$

$$[\bar{F}_{BL}(\bar{C}_{rb})]_i = [\bar{F}_{GRD}(\bar{C}_{rb})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ . \tag{5.25e}$$

4. BOTTOM completes the computational sequence of successive updating scheme for

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{BOT}(\bar{C}_{rw})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ , \tag{5.26a}$$

$$[\bar{F}_{BL}(\bar{C}_{rb})]_i = [\bar{F}_{BOT}(\bar{C}_{rb})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ . \tag{5.26b}$$

5. SURFAC completes the computational sequence of successive updating scheme for

$$[\bar{F}(\bar{H})]_i = [\bar{F}_{SRF}(\bar{H})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ , \tag{5.27a}$$

$$[\bar{F}(\bar{G}_x)]_{i-\frac{1}{4}} = [\bar{F}_{SRF}(\bar{G}_x)]_{i-\frac{1}{4}} \ , \ \text{for all upstream half-elements } (i - \tfrac{1}{4}) = 1, \ldots, N \ , \tag{5.27b}$$

$$[\bar{F}(\bar{G}_x)]_{i+\frac{1}{4}} = [\bar{F}_{SRF}(\bar{G}_x)]_{i+\frac{1}{4}} \ , \ \text{for all downstream half-elements } (i + \tfrac{1}{4}) = 1, \ldots, N \ , \tag{5.27c}$$

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{SRF}(\bar{C}_{rw})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ . \tag{5.27d}$$

6. STREAM completes the computational sequence of successive updating scheme for

$$[\bar{F}(\bar{H})]_i = [\bar{F}_{SRM}(\bar{H})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ , \tag{5.28a}$$

$$[\bar{F}(\bar{G}_x)]_{i-\frac{1}{4}} = [\bar{F}_{SRM}(\bar{G}_x)]_{i-\frac{1}{4}} \ , \ \text{for all upstream half-elements } (i - \tfrac{1}{4}) = 1, \ldots, N \ , \tag{5.28b}$$

$$[\bar{F}(\bar{G}_x)]_{i+\frac{1}{4}} = [\bar{F}_{SRM}(\bar{G}_x)]_{i+\frac{1}{4}} \ , \ \text{for all downstream half-elements } (i + \tfrac{1}{4}) = 1, \ldots, N \ , \tag{5.28c}$$

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{SRM}(\bar{C}_{rw})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ , \tag{5.28d}$$

$$[\bar{F}_{BL}(\bar{C}_{rb})]_i = [\bar{F}_{SRM}(\bar{C}_{rb})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ . \tag{5.28e}$$

7. PLANTS completes the computational sequence of successive updating scheme for

$$[\bar{F}(\bar{H})]_i = [\bar{F}_{PLT}(\bar{H})]_i \ , \text{ for all elements } i = 1, ..., N \ , \qquad (5.29a)$$

$$[\bar{F}(\bar{G}_x)]_{i-\frac{1}{4}} = [\bar{F}_{PLT}(\bar{G}_x)]_{i-\frac{1}{4}} \ , \text{ for all upstream half-elements } (i - \tfrac{1}{4}) = 1, ..., N \ , \qquad (5.29b)$$

$$[\bar{F}(\bar{G}_x)]_{i+\frac{1}{4}} = [\bar{F}_{PLT}(\bar{G}_x)]_{i+\frac{1}{4}} \ , \text{ for all downstream half-elements } (i + \tfrac{1}{4}) = 1, ..., N \ , \qquad (5.29c)$$

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{PLT}(\bar{C}_{rw})]_i \ , \text{ for all elements } i = 1, ..., N \ , \qquad (5.29d)$$

$$[\bar{F}_{BL}(\bar{C}_{rb})]_i = [\bar{F}_{PLT}(\bar{C}_{rb})]_i \ , \text{ for all elements } i = 1, ..., N \qquad (5.29e)$$

8. RADIOR completes the computational sequence of successive updating scheme for

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{RAD}(\bar{C}_{rw})]_i \ , \text{ for all elements } i = 1, ..., N \ , \qquad (5.30a)$$

$$[\bar{F}_{BL}(\bar{C}_{rb})]_i = [\bar{F}_{RAD}(\bar{C}_{rb})]_i \ , \text{ for all elements } i = 1, ..., N \qquad (5.30b)$$

It is important to point out that, since the sequential computational method is based on a successive updating scheme for the calculations of the $5N$ number of right-hand-side solution functions [Eqs. (5.23a)–(5.30b)], the computational solution algorithm of the RADONE computer code requires computer core storage only for the $5N$ number of right-hand-side solution functions, without requiring any additional computer core storage for the individual phenomenological parts.

Considering that the general computational algorithm of the RADONE computer also includes a user-specified option for excluding the solution of hydrodynamic conditions by incorporating already computed and stored results of water surface elevation $\bar{H}_i$ in element i and channel flow rates $\bar{G}_{x;i-\frac{1}{4}}$ in the upstream half-element $i - \frac{1}{4}$ and $\bar{G}_{x;i+\frac{1}{4}}$ in the downstream half-element $i + \frac{1}{4}$ (Sect. 4.9), the sequential computational procedure controlled by the major solution subroutine SOLVER uses a modified and limited successive updating scheme for the particular user-specified option. For the user-specified option that considers specified hydrodynamic conditions (Sect. 4.9), the major solution subroutine SOLVER first calls an auxiliary subroutine FLOWER, which generates, based on specified input data, the conditions for (1) the water surface elevation $\bar{H}_i$ in all elements $i = 1, ..., N$, (2) the channel flow rate $\bar{G}_{x;i-\frac{1}{4}}$ in all upstream elements $(i - \frac{1}{4}) = 1, ..., N$, and (3) the channel flow rate $\bar{G}_{x;i+\frac{1}{4}}$ in all downstream half-elements $(i + \frac{1}{4}) = 1, ..., N$. The major solution subroutine SOLVER then calls successively the eight major subroutines (CONVEC, TURBUL, GROUND, BOTTOM, SURFAC, STREAM, PLANTS, and RADIOR), which successively calculate the contributions of at most eight phenomenological effects that control the variations of the conditions associated with only two principal solution variables, consisting of (1) the water concentration of the radionuclide in the water layer $\bar{C}_{rw;i}$ in all elements $i = 1, ..., N$ and (2) the bottom concentration of the radionuclide in the bottom layer $\bar{C}_{rb;i}$ in all elements $i = 1, ..., N$.

1. For optional specified hydrodynamic conditions, CONVEC completes the partial computational sequence of the successive updating scheme only for

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{CNV}(\bar{C}_{rw})]_i \ , \text{ for all elements } i = 1, ..., N \qquad (5.31)$$

2. For optional specified hydrodynamic conditions, TURBUL completes the partial computational sequence of the successive updating scheme only for

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{TRB}(\bar{C}_{rw})]_i \ , \text{ for all elements } i = 1, ..., N \qquad (5.32)$$

3. For optional specified hydrodynamic conditions, GROUND completes the partial computational sequence of the successive updating scheme only for

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{GRD}(\bar{C}_{rw})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ , \tag{5.33a}$$

$$[\bar{F}_{BL}(\bar{C}_{rb})]_i = [\bar{F}_{BL}(\bar{C}_{rb})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ , \tag{5.33b}$$

4. For optional specified hydrodynamic conditions, BOTTOM completes the standard computational sequence of the successive updating scheme [Eqs. (5.26a) and (5.26b)],
5. For optional specified hydrodynamic conditions, SURFAC completes the partial computational sequence of the successive updating scheme only for

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{SRF}(\bar{C}_{rw})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ . \tag{5.34}$$

6. For optional specified hydrodynamic conditions, STREAM completes the partial computational sequence of the successive updating scheme only for

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{PLT}(\bar{C}_{rw})]_i \ , \ \text{for all elements } i = 1, \ldots, N \ , \tag{5.35a}$$

$$[\bar{F}_{BL}(\bar{C}_{rb})]_i = [\bar{F}_{PLT}(\bar{C}_{rb})]i \ , \ \text{for all elements } i = 1, \ldots, N \ . \tag{5.35b}$$

7. For optional specified hydrodynamic conditions, PLANTS completes the partial computational sequence of the successive updating scheme only for

$$[\bar{F}_{WL}(\bar{C}_{rw})]_i = [\bar{F}_{PLT}(\bar{C}_{rw})] \ , \ \text{for all elements } i = 1, \ldots, N \ , \tag{5.36a}$$

$$[\bar{F}_{BL}(\bar{C}_{rb})]_i = [\bar{F}_{PLT}(\bar{C}_{rb})] \ , \ \text{for all elements } i = 1, \ldots, N \tag{5.36b}$$

8. For optional specified hydrodynamic conditions, RADIOR completes the standard computational sequence of the successive updating scheme [Eqs. (5.30a) and (5.30b)].

An extensive and more detailed outline of the general computational solution algorithm, based on the successive updating scheme, of the fast-transient, one-dimensional, discrete-element transport models of UTA is presented in the users manual of the ESTONE computer code for simulating hydrodynamic, water temperature, and salinity conditions in controlled rivers and tidal estuaries [Eraslan (1983)].

The fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)] is used in the present version of RADONE in order to be able to calculate accurately the fast radiological decay rates that may need to be considered in the simulation of the transport conditions for certain radionuclides with relatively short half-life times. Furthermore, the fourth-order Runge-Kutta-Gill method also guarantees the conditional stability of the numerical solutions of the hydrodynamic conditions and the radionuclide concentration conditions both according to the second-upwind-differencing formulation of the convective transport terms and according to the general formulation of the nonconvective transport terms which consist of the convection-defect transport terms and the eddy-turbulent transport terms.

However, it should be pointed out that the numerical solution of the governing computational system of discrete-element equations [Eqs. (5.1a)–(5.5b)], by utilizing the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)], can definitely introduce numerical errors in the solution, particularly in the forms of artificial numerical dispersion effects in the solution of the channel flow rate $\overline{G}_x$ and in the solution of the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, according to the computational subsystem of (1) the discrete-element equation for channel flow rate $\overline{G}_{x;i-\frac{1}{4}}$ in the upstream half-element $i - \frac{1}{4}$ [Eq. (5.2a)], (2) the discrete-element equation for channel flow rate $\overline{G}_{x;i+\frac{1}{4}}$ in the downstream half-element $i + \frac{1}{4}$ [Eq. (5.3a)], and (3) the discrete-element equation for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eq. (5.4a)]. Therefore, the RADONE computer code should be used only after carefully considering the possible influences of the numerical dispersion effects on the computer simulation results of the channel flow rate $\overline{G}_x$ and the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, based on considerations of the general site-specific flow characteristics in the main flow channel and the specified value of the time step of numerical integration (Sect. 5.3). The numerical dispersion effects that result as consequences of the computational solution algorithm, based on the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)], can possibly be eliminated by utilizing the composite time-splitting algorithm used in more advanced, multidimensional, discrete-element mathematical transport models [e.g., Eraslan, Lin, and Sharp (1983)] of the UTA project.

5.3 CONSIDERATION OF STABILITY OF NUMERICAL SOLUTIONS

The complete set of criteria required for the stability of the numerical solution of the governing system of discrete-element equations, consisting of (1) computational subsystem of discrete-element equations for water surface elevation $\overline{H}_i$ in element i [Eqs. (2.1), (5.1a), and (5.1b)], (2) computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i-\frac{1}{4}}$ in the upstream element $i - \frac{1}{4}$ [Eqs. (2.2), (5.2a), and (5.2b)], (3) computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i+\frac{1}{4}}$ in the downstream half-element $i + \frac{1}{4}$ [Eqs. (2.3), (5.3a), and (5.3b)], (4) computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)], and (5) computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)] can be obtained formally (a) first by considering the subset of stability criteria required for the solution of each computational subsystem, separately, and (b) second by considering the relational consequences, based on comparisons, of the different subsets of stability criteria required for the solution of different computational subsystems, together. The present considerations of the stability characteristics of the numerical solutions will be based on formally established results; the detailed and rigorous development of each stability criterion for each subsystem of discrete-element equations will not be presented.

5.3.1 Consideration of the Stability of the Numerical Solution of the Computational Subsystem for Hydrodynamic Conditions

The stability of the numerical solution of the computational subsystem for hydrodynamic conditions, consisting of (1) computational subsystem of discrete-element equations for water surface elevation $\overline{H}_i$ in element i [Eqs. (2.1), (5.1a), and (5.1b)], (2) computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i-\frac{1}{4}}$ in the upstream half-element $i - \frac{1}{4}$ [Eqs. (2.2), (5.2a), and (5.2b)], and (3) computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i+\frac{1}{4}}$ in the downstream half-element $i + \frac{1}{4}$ [Eqs. (2.3), (5.3a), and (5.3b)], are discussed in detail in the users manual of the computer code ESTONE [Eraslan (1983)] associated with the fast-transient, one-dimensional discrete-element model for simulating hydrodynamic, water temperature, and salinity conditions in controlled rivers and tidal estuaries.

The "necessary and sufficient" stability criterion associated with the maximum allowable time step for the numerical solution of hydrodynamic conditions $\Delta t\{\overline{H},\overline{G}_x\}$ becomes

$$\Delta t\{\overline{H},\overline{G}_x\} \leqslant \frac{1}{2(\overline{R}_{x;i,i\pm1})_{\max}} \; \frac{(\Delta x_i)_{\min}}{[(\overline{v}_{\omega;i})_{\max} + (|\overline{V}_{x;i}|)_{\max}]} \; . \tag{5.37}$$

The effect of the unequal curvilinear lengths of the adjacent elements Δx_i and $\Delta x_{i\pm1}$ is included in the formulation of the necessary and sufficient stability criterion for the numerical solution of the hydrodynamic conditions [Eq. (5.37)] as the ratio of the curvilinear lengths of the adjacent elements Δx_i and $\Delta x_{i\pm1}$, with the maximum ratio $(\overline{R}_{x;i,i\pm1})_{\max}$ defined as

$$(\overline{R}_{x;i,i\pm1})_{\max} = \max\left[\left(\frac{\Delta x_i}{\Delta x_{i\pm1}}\right) \text{ or } \left(\frac{\Delta x_{i\pm1}}{\Delta x_i}\right)\right] \; . \tag{5.38}$$

Values of surface wave speed $\overline{v}_\omega$ (celerity) associated with the surface wave phenomenon in (1) the upstream half-element $i - ¼$, (2) element i, and (3) the downstream half-element $i + ¼$ can be formulated based on depth conditions in the two half-elements $i \pm ¼$ and element i. These depth conditions consist of

1. the sum of the mean water level depth $\overline{D}_{mwl;i-¼}$ (relative to the arbitrarily specified level) and the water surface elevation difference $\overline{H}_{mwl;i-¼}$ (relative to the mean water level) in the upstream half-element $i - ¼$,
2. the sum of the mean water level depth $\overline{D}_{mwl;i}$ and the water surface elevation difference $\overline{H}_{mwl;i}$ in element i, and
3. the sum of the mean water level depth $\overline{D}_{mwl;i+¼}$ and the water surface elevation difference $\overline{H}_{mwl;i+¼}$ in the downstream half-element $i + ¼$.

Values of surface wave speed can be calculated as

$$\overline{v}_{\omega;i\pm¼} = \sqrt{[g_a\overline{D}_{i\pm¼}]} = \sqrt{[g_a(\overline{D}_{mwl;i\pm¼} + \overline{H}_{mwl;i\pm¼})]} \; , \tag{5.39a}$$

$$\overline{v}_{\omega;i} = \sqrt{[g_a\overline{D}_i]} = \sqrt{[g_a(\overline{D}_{mwl;i} + \overline{H}_{mwl;i})]} \; . \tag{5.39b}$$

Considering that depth conditions are interpolated within element i, both in the upstream half-element $i - ¼$ and in the downstream half-element $i + ¼$, for the analysis of numerical stability conditions, it is generally sufficient to consider a representative surface wave speed $\overline{v}_{\omega;i}$ in element i that is approximately equal to the surface wave speed $\overline{v}_{\omega;i-¼}$ in the upstream half-element $i - ¼$ and $\overline{v}_{\omega;i+¼}$ in the downstream half-element $i + ¼$. Therefore, the maximum value of the representative surface wave speed can be considered as

$$(\overline{v}_{\omega;i\pm¼})_{\max} \simeq (\overline{v}_{\omega;i})_{\max} \; , \tag{5.40a}$$

i.e.,

$$\max[\overline{v}_{\omega;i\pm¼}] \simeq \max[\overline{v}_{\omega;i}] \; . \tag{5.40b}$$

The necessary and sufficient stability criterion for determining the maximum allowable time step for the numerical solution of hydrodynamic conditions $\Delta t\{\overline{H},\overline{G}_x\}$ [Eqs. (5.37)–(5.40b)] must be satisfied during each time step of the numerical solution of the hydrodynamic part of the discrete-element mathematical transport model.

It should be pointed out that the numerical solution of the computational subsystem for hydrodynamic conditions [Eqs. (2.1)–(2.3) and (5.1a)–(5.3b)], by utilizing the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)], can introduce numerical errors in the solution, particularly in the forms of artificial numerical dispersion effects in the solutions of the water surface elevation $\overline{H}_i$ and the channel flow rate $\overline{G}_{x;i\pm 1/2}$. The numerical dispersion effects that result as consequences of the computational solution algorithm, based on the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)] can be partially eliminated by considering the composite time-splitting algorithm used in more advanced multidimensional, discrete-element mathematical transport models [e.g., Eraslan, Lin, and Sharp (1983)] of the UTA project.

5.3.2 Consideration of the Stability of the Numerical Solution of the Computational Subsystem of Discrete-Element Equations for Water Concentration of the Radionuclide in the Water Layer

The computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in the element i [Eqs. (2.4), (5.4a), and (5.4b)] can first be considered as an independent computational system that is discretized only along the curvilinear longitudinal x-axis of the main flow channel, with only a single water layer between the bottom and the water surface of the main flow channel and, hence, without any spatial discretization along the geophysical vertical z-axis. However, it is important to note that, since there definitely exist conditions that lead to the transport of the radionuclide between the water layer and the bottom layer, particularly in the forms of bottom-settling (deposition) radionuclide transport flux and bottom-resuspension (scouring) radionuclide transport flux (Sect. 3.5), the general formulation of the transient, one-dimensional radionuclide transport model, in the general sense, includes a two-layer form of spatial discretization of the local depth along the geophysical vertical z-axis (Figs. 3.1a–3.2b). The additional effects of the vertical transport of the radionuclide, between the water layer and the bottom layer, on the stability of the numerical solution of the two computational subsystems, consisting of (1) computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)] and (2) computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)] will also be considered after establishing separately the stability criterion for each individual computational subsystem.

Considering the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in the element i [Eqs. (2.4), (5.4a), and (5.4b)], the stability of the numerical solution depends on the one-dimensional formulation of the radionuclide transport effects, consisting of (1) the convective radionuclide transport effects (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (2.4) and (2.5)] and (2) the nonconvective radionuclide transport effects (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (2.4), (2.6), and (3.68)]. The convective transport effect criterion associated with the convective radionuclide transport effects (along the curvilinear longitudinal x-axis of the main flow channel) [Eqs. (2.4) and (2.5)] can be formulated as the one-dimensional, standard form of the Courant criterion [e.g., Roache (1972)]. Hence, the maximum allowable time step for the numerical solution of the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, based on the convective transport effect criterion, becomes

$$\Delta t\{\overline{C}_{rw}\}_{CNV} \leqslant \min\left[\frac{\Delta x_i}{|\overline{V}_{x;i\pm½}|}\right] . \tag{5.41}$$

The effect of the unequal curvilinear lengths of the adjacent elements Δx_i and $\Delta x_{i\pm 1}$ can be introduced in the formulation of a convenient and stronger form (i.e., more restrictive) of the convective transport effect criterion, by considering (1) the value of the channel flow velocity $\overline{V}_{x;i}$ at the center of the element i and (2) the ratio of the curvilinear lengths of the adjacent elements Δx_i and $\Delta x_{i\pm 1}$, based on the maximum $(\overline{R}_{x;i,i\pm 1})_{\max}$ [Eq. (5.38)], as

$$\Delta t\{\overline{C}_{rw}\}_{CNV} \leqslant \min\left[\frac{\Delta x_i}{(\overline{R}_{x;i,i\pm 1})_{\max}|\overline{V}_{x;i}|}\right] \tag{5.42}$$

The simplest and strongest (i.e., most restrictive) necessary and sufficient form of the convective transport effect criterion, associated with the maximum allowable time step for the numerical solution of the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, can be formulated as

$$\Delta t\{\overline{C}_{rw}\}_{CNV} \leqslant \frac{(\Delta x_i)_{\min}}{(\overline{R}_{x;i,i\pm 1})_{\max}(|\overline{V}_{x;i}|)_{\max}} \tag{5.43}$$

It is important to point out that in applications to problems which require simultaneous solutions of the flow and radionuclide concentration conditions in a controlled river or a tidal estuary, the necessary and sufficient form of the convective transport effect criterion for the numerical solution of the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ [Eq. (5.43)] and the necessary and sufficient stability criterion for the numerical solution of the hydrodynamic conditions [Eq. (5.37)], consisting of water surface elevation $\overline{H}_i$ and the channel flow rate $\overline{G}_{x;i}$, cannot be established a priori, because the specifications of the maximum allowable time step for the numerical solutions [Eqs. (5.37) and (5.42) or (5.43)] includes implicitly the unknown flow variable of the solution, channel flow velocity $\overline{V}_{x;i}$ in the element i of the channel segment. Therefore, in applications to problems that require simultaneous solutions of the flow and radionuclide concentration conditions, it becomes necessary to estimate a first-order approximation for the absolute value of maximum channel flow velocity $(|\overline{V}_{x;i}|)_{\max}$ [Eqs. (5.37) and (5.42) or (5.43)] based on careful consideration of the physical flow conditions in a controlled river or a tidal estuary. The detailed discussions for determining accurately the first-order approximation of the absolute value of maximum channel flow velocity $(|\overline{V}_{x;i}|)_{\max}$ [Eqs. (5.37) and (5.43)] are presented in the users manual of ESTONE computer code associated with the fast-transient (tidal-transient), one-dimensional, discrete-element model for simulating hydrodynamic, water temperature, and salinity conditions in controlled rivers and tidal estuaries [Eraslan (1983)] and, therefore, will not be repeated in this report. The point that needs to be emphasized is that, in applications to problems which require simultaneous solutions of the flow and radionuclide concentration conditions, a reasonably accurate first-order approximation of the absolute value of maximum channel flow velocity $(|\overline{V}_{x;i}|)_{\max}$ is required for establishing the necessary and sufficient criterion for the numerical solution of the radionuclide concentration conditions in a river or an estuary.

On the other hand, for the numerical solution of only the radionuclide concentration conditions, by using optional specified input data (Sect. 4.9), for water surface elevation $\overline{H}_i$ in the element i and for the channel flow rates $\overline{G}_{x;i-¼}$ and $\overline{G}_{x;i+¼}$ in the upstream half-element $i - ¼$ and in the downstream half-element

$i + ¼$, respectively, the necessary and sufficient stability criterion for the numerical solution of the water concentration of the radionuclide in the water layer $\mathcal{C}_{rw}$ [Eq. (5.42) or (5.43)] can be established a priori because the absolute value of maximum channel flow velocity $(|\mathcal{V}_{x;i}|)_{\max}$ can be determined from the specified input data for hydrodynamic conditions (Sect. 4.9) at each time level of the numerical solution. Hence, in applying RADONE to the simulation of the radionuclide concentration conditions in a river or an estuary, by using optional specified input data for hydrodynamic conditions (Sect. 4.9), the user can readily determine the specified time step Δt of the numerical solution, based on specified input data for flow conditions in the main flow channel.

The necessary and sufficient stability criterion, based on the convective transport effect criterion, for determining the maximum allowable time step $\Delta t\{\mathcal{C}_{rw}\}_{CNV}$ for the numerical solution of the water concentration of the radionuclide in the water layer $\mathcal{C}_{rw}$ [Eq. (5.42) or (5.43)] must be satisfied during each time step of the numerical solution of the discrete-element mathematical transport model.

The present version of the computational algorithm of the fast-transient, one-dimensional, two-layer radionuclide transport model and its associated computer code RADONE utilizes a fourth-order, Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)], which is based on temporally multilevel calculations that represent a special time-splitting procedure [e.g., Roache (1972)]. Therefore, based on considerations of the nonconvective radionuclide transport effects (Sect. 3.4), which consist of the convection-defect radionuclide transport effect and eddy-turbulent radionuclide transport effect, the use of the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)] guarantees the stability of the numerical solutions, provided that the necessary and sufficient stability criterion, based on the convective transport effect criterion [Eq. (5.42) or (5.43)], is satisfied. Hence, for most controlled rivers and tidal estuaries, it becomes unnecessary to consider the nonconvective radionuclide transport effects (Sect. 3.4); and it only becomes necessary to consider the convective transport effect criterion [Eq. (5.42) or (5.43)] for the numerical solution of the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer [Eqs. (2.4), (5.4a), and (5.4b)].

It is again important to point out that the numerical solution of the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer [Eqs. (2.4), (5.4a), and (5.4b)], by utilizing the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)], can introduce numerical errors in the solution, particularly in the forms of artificial numerical dispersion effects in the solution of the water concentration of the radionuclide in the water layer $\mathcal{C}_{rw}$. Again, the numerical dispersion effects that result as consequences of the computational solution algorithm, based on the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)], can be partially eliminated by considering the composite time-splitting algorithm used in more advanced, multidimensional, discrete-element mathematical transport models [e.g., Eraslan, Lin, and Sharp (1983)] of the UTA project.

5.3.3 Consideration of the Stability of the Numerical Solution of the Computational Subsystem of Discrete-Element Equations for Bottom Concentration of the Radionuclide in the Bottom Layer

The computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\mathcal{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)] consists of discrete-element equations that include neither convective radionuclide transport terms nor nonconvective (i.e., combination of convection-defect and eddy-turbulent) radionuclide transport terms, according to the general formulation of the fast-transient, one-dimensional, two-layer radionuclide transport model. Therefore, according to the present version of the computational algorithm for the numerical solution of the radionuclide concentration conditions, the use of the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)], effectively guarantees the stability and, hence, effectively eliminates the need for any stability criterion for the solution of the computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)].

5.3.4 Consideration of the Effect of Vertical Bottom Radionuclide Transport on the Stability of the Numerical Solution of the Combined Subsystem of Discrete-Element Equations for Radionuclide Concentration Conditions

The formulation of the combined subsystem of discrete-element equations for radionuclide concentration conditions, consisting of (1) the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)] and (2) the computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)], in the general sense represents a two-layer division of the depth of the main flow channel along the geophysical vertical z-axis. Also, considering that the bottom-settling (deposition) radionuclide transport flux $\overline{g}_{rw,fall}$ [Eq. (3.74)] in a sense represents a convective radionuclide transport flux out of the water layer, this term can possibly behave as a convective transport effect, along the geophysical z-axis, which can influence the stability of the numerical solution of the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)]. Therefore, although a complete stability analysis of the combined computational subsystem of discrete-element equations for radionuclide concentration conditions [Eqs. (2.4), (2.16), and (5.4a)–(5.5b)] is not yet established, it may be required to consider a bottom transport effect criterion, as a secondary importance criterion, to guarantee the stability of the numerical solution of the water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i.

The formulation of the bottom-settling radionuclide transport flux [Eq. (3.74)] can be considered as including a fundamental part, which represents the bottom-settling (deposition) velocity, along the geophysical vertical z-axis, which transports the water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ out of the water layer of element i, depending on the bottom-settling effect of the radionuclide from the water layer into the bottom layer, as

$$V_{rw,bot} = R_{w,fall} \quad \frac{\overline{V}_{rw,fall}}{[1 + (|\overline{V}_x| / \overline{V}_{ref,fall})^{p_{fall}}]} \tag{5.44}$$

Hence, a plausible bottom transport effect criterion can be formally considered as a generalized Courant criterion [e.g., Roache (1972)], based on the local depth of the main flow channel D_i and the bottom-settling (deposition) transport velocity $V_{rw,bot}$ [Eq. (5.44)], along the geophysical vertical z-axis. The maximum allowable time step for the numerical solution of the water concentration of the radionuclide in the water layer, based on the bottom transport effect criterion, becomes

$$\Delta t \{\overline{C}_{rw}\}_{bot} \leqslant \min \left[\frac{\overline{D}_i}{V_{rw,bot;i}} \right] \tag{5.45}$$

A more convenient and stronger (i.e., more restrictive) form of the necessary and sufficient bottom transport effect criterion can also be formally considered as

$$\Delta t\{\overline{C}_{rw}\}_{bot} \leqslant \frac{(\overline{D}_i)_{\min}}{R_{w,fall}\, V_{rw,fall}} \ , \tag{5.46}$$

which depends on the minimum depth of the main flow channel and the specified constant coefficient of effective fall speed and the effective fall velocity associated with the lumped sediment-organic-matter class (Sect. 3.5).

It is important to note that the effect of the bottom-resuspension (scouring) radionuclide transport flux $\overline{g}_{rw,susp}$ [Eq. (3.79)] on the stability of the numerical solution of the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ cannot be considered similar to the formal consideration of the effect of the bottom-settling (deposition) radionuclide transport flux $\overline{g}_{rw,fall}$ [Eq. (3.74)]. Since the formulation of the bottom-resuspension (scouring) radionuclide transport flux $\overline{g}_{rw,susp}$ [Eq. (3.79)] is based on the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb}$, but not on the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, another form of bottom transport effect criterion, based on formal considerations of the Courant number criterion [e.g., Roache (1972)], cannot be established for the numerical solution of the water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i for the solution of the radionuclide concentration conditions in the main flow channel.

Since a complete, rigorous stability analysis of the combined subsystem of discrete-element equations for radionuclide concentration conditions, consisting of (1) the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)] and (2) the computational subsystem of discrete-element equations for the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)], cannot be established, the necessity for the satisfaction of the bottom transport effect criterion [Eqs. (5.45) and (5.46)] also cannot be established. Hence, it may be possible to obtain stable numerical solutions of the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ with numerical integration time steps Δt greater than the maximum allowable time step of numerical integration associated with the bottom transport effect criterion [Eqs. (5.45) and (5.46)]. However, it is important to consider the bottom transport effect criterion [Eqs. (5.45) and (5.46)] as a secondary, in a sense precautionary, measure, in the event that the numerical solution of the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)] start exhibiting unstable behavior during the numerical integration of the subsystem with a time step of numerical integration, only according to the maximum allowable time step of numerical integration, associated with the convective transport effect criterion [Eqs. (5.41)–(5.43)].

5.3.5 Consideration of the Effect of Radiological Decay Rate on the Accuracy of the Numerical Solution of the Combined Subsystem of Discrete-Element Equations for Radionuclide Concentration Conditions

The stable behavior of the numerical solutions of the combined subsystem of discrete-element equations for radionuclide concentration conditions, consisting of (1) computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)] and (2) computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)], based on numerical integration procedures, which are in complete compliance with the two stability criteria [Eqs. (5.41)–(5.46)], does not necessarily guarantee, in the general sense, the convergence accuracy of the numerical solutions of the radionuclide concentrations, because the effects of the local radiological decay conditions can be the dominant computational effect, particularly for certain radionuclides with relatively fast radiological decay rates (Sect. 3.8). Therefore, the maximum allowable time step of numerical integration Δt, determined according to the two sets of stability criteria [Eqs. (5.41)–(5.46)] can become too large for certain radionuclides with relatively fast decay rates (Sect. 3.8).

Considering the first-order form of the radiological decay rate [Eqs. (3.12a) and (3.12b)], the standard truncation error criterion for the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)] establishes that the percent truncation error is bounded by the product of the maximum absolute value of the fourth-order derivative of the solution and the fourth power of the time step of numerical integration Δt. Therefore, considering the first-order forms of the radiological decay rates [Eqs. (3.12a) and (3.12b)], a plausible nuclear decay effect criterion can be formulated, based on the specified maximum allowable percent error for the numerical solution of radionuclide concentrations $E_{\max,rw,rb}$, as

$$\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_{nuc} \leqslant \frac{(E_{\max,rw,rb})^{1/4}}{r_{nuc}} \quad . \tag{5.47}$$

The nuclear decay effect criterion can also be represented in terms of the specified half-life $t_{1/2,nuc}$ of the radionuclide [Eqs. (3.12a) and (3.12b)] as

$$\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_{nuc} \leqslant \frac{(E_{\max,rw,rb})^{1/4}}{(\ln 2/t_{1/2,nuc})} \leqslant 1.4427(E_{\max,rw,rb})^{1/4}\, t_{1/2,nuc} \quad , \tag{5.48a}$$

or approximately as

$$\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_{nuc} \leqslant (E_{\max,rw,rb})^{1/4}\, t_{1/2,nuc} \quad . \tag{5.48b}$$

Hence, for any specified maximum allowable percent error $E_{\max,rw,rb}$ for the numerical solutions of the radionuclide concentrations, associated with the accurate numerical integration of the radiological decay rates (Sect. 3.8), it is possible to determine an appropriate time step of numerical integration according to the nuclear decay effect criterion [Eqs. (5.47), (5.48a), and (5.48b)], which is independent of the previously established two stability criteria, consisting of (1) convective transport effect criterion [Eqs. (5.41)–(5.43)] and (2) bottom transport effect criterion [Eqs. (5.44)–(5.46)].

5.3.6 Summary Considerations of Stability Criteria for the Numerical Solution

Considering all the phenomenological effects that can control the stability of the numerical solutions of the complete discrete-element system, consisting of (1) the computational subsystem of discrete-element equations for water surface elevation $\overline{H}_i$ in element i [Eqs. (2.1), (5.1a), and (5.1b)], (2) the computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i-1/4}$ in the upstream half-element $i - 1/4$ [Eqs. (2.2), (5.2a), and (5.2b)], (3) the computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i+1/4}$ in the downstream half-element $i + 1/4$ [Eqs. (2.3), (5.3a), and (5.3b)], (4) the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)], and (5) the computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)], the results can be summarized in terms of four practical stability criteria for determining the maximum allowable time step of computation Δt, associated with the selected numerical integration algorithm based on the fourth-order Runge-Kutta-Gill method [e.g., Conte and deBoor (1972)].

1. Primary Stability Criterion for Hydrodynamic Conditions:

$$\Delta t\{\overline{H},\overline{G}_x\}_1 \leq \frac{1}{2(\overline{R}_{x;i,i\pm1})_{\max}} \, \frac{(\Delta x_i)_{\min}}{[(\overline{v}_{\omega;i})_{\max} + (|\overline{V}_{x;i}|)_{\max}]} \ . \tag{5.49}$$

2. Primary Stability Criterion for Radionuclide Concentration Conditions (Convective Transport Effect Criterion):

$$\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_1 \leq \frac{(\Delta x_i)_{\min}}{(\overline{R}_{x;i,i\pm1})_{\max}(|\overline{V}_{x;i}|)_{\max}} \ . \tag{5.50}$$

3. Secondary Stability Criterion for Radionuclide Concentration Conditions (Bottom Transport Effect Criterion):

$$\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_{2,bot} \leq \frac{(\overline{D}_i)_{\min}}{R_{w,fall}\, V_{rw,fall}} \ . \tag{5.51}$$

4. Accuracy Criterion for Radionuclide Concentration Conditions (Nuclear Decay Effect Criterion):

$$\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_{2,nuc} \leq (E_{\max,rw,rb})^{1/4}\, t_{1/2,nuc} \ . \tag{5.52}$$

Hence, a computational time step Δt, which is in compliance with all four practical stability criteria [Eqs. (4.49)–(5.52)], will guarantee stable and approximately accurate numerical solution of the complete system of discrete-element equations [Eqs. (2.1)–(2.4), (2.16), and (5.1a)–(5.5b)].

The difference between (1) the primary stability criterion for hydrodynamic conditions $\Delta t\{\overline{H},\overline{G}_x\}_1$ [Eq. (5.49)] and (2) the primary stability criterion for radionuclide concentration conditions $\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_1$ [Eq. (5.50)] can be represented as the ratio of the maximum allowable time steps $R(\Delta t)$, associated with the numerical solutions, as

$$R(\Delta t) = \frac{\Delta t\{\overline{H},\overline{G}_x\}_1}{\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_1} \simeq \frac{(|\overline{V}_{x;i}|)_{\max}}{2[(\overline{v}_{\omega;i})_{\max} + (|\overline{V}_{x;i}|)_{\max}]} \ , \tag{5.53}$$

or in rearranged form as

$$R(\Delta t) = \frac{\Delta t\{\overline{H},\overline{G}_x\}_1}{\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_1} = \frac{1}{2\{1 + [(\overline{v}_{\omega;i})_{\max}/(|\overline{V}_{x;i}|)_{\max}]\}} \ . \tag{5.54}$$

The ratio of the absolute value of maximum channel flow velocity $(|\overline{V}_{x;i}|)_{\max}$ to maximum surface wave speed $(\overline{v}_{\omega;i})_{\max}$ [Eq. (5.39b)] represents, in a sense, a critical Froude number [e.g., Daily and Harleman (1966), Harleman (1966), Dronkers (1964)] as

$$(Fr)_{cr} = \frac{(|\overline{V}_{x;i}|)_{\max}}{(\overline{v}_{\omega;i})_{\max}} = \frac{(|\overline{V}_{x;i}|)_{\max}}{\sqrt{g_a(\overline{D}_i)_{\max}}} = \frac{(|\overline{V}_{x;i}|)_{\max}}{\sqrt{g_a[(\overline{D}_{mwl;i})_{\max} + (\overline{H}_{mwl;i})_{\max}]}} \tag{5.55}$$

Hence, by substituting the critical Froude number $(Fr)_{cr}$ [Eq. (5.55)], the definition of the ratio of the maximum allowable time steps $R(\Delta t)$ [Eqs. (5.53) and (5.54)] can be reformulated as

$$R(\Delta t) = \frac{\Delta t\{\overline{H},\overline{G}_x\}_1}{\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_1} = \frac{(Fr)_{cr}}{2[1 + (Fr)_{cr}]} \tag{5.56}$$

In general, for a large controlled-flow river or a large tidal-dominated estuary, the critical Froude number $(Fr)_{cr}$ [Eq. (5.55)], based on normal flow conditions in the main flow channel, is much less than 1. Hence, the definition of the ratio of the maximum allowable time steps $R(\Delta t)$ [Eq. (5.70)] can be approximated as

$$R(\Delta t) = \frac{\Delta t\{\overline{H},\overline{G}_x\}_1}{\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_1} = \frac{(Fr)_{cr}}{2} \quad , \text{ for } (Fr)_{cr} \ll 1 \tag{5.57}$$

The comparison of (1) the primary stability criterion for hydrodynamic conditions $\Delta t\{\overline{H},\overline{G}_x\}_1$ [Eq. (5.49)] and (2) the primary stability criterion for radionuclide concentration conditions $\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_1$ [Eq. (5.50)], as the ratio of the maximum allowable time steps $R(\Delta t)$ [Eqs. (5.56) and (5.57)], clearly indicates that the maximum allowable time step for the numerical solution of hydrodynamic conditions is much smaller than the maximum allowable time step for the numerical solution of the radionuclide concentration conditions in a typical controlled river or tidal estuary, with critical Froude number $(Fr)_{cr}$ generally much smaller than 1 [Eq. (5.57)]. Hence, in the application of RADONE to a typical controlled river or a tidal estuary, the computation of the hydrodynamic conditions, according to the numerical solution of (1) the computational subsystem of discrete-element equations for water surface elevation $\overline{H}_i$ in element i [Eqs. (2.1), (5.1a), and (5.1b)], (2) the computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i-1/4}$ in upstream half-element $i - 1/4$ [Eqs. (2.2), (5.2a), and (5.2b)], and (3) the computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i+1/4}$ in downstream half-element $i + 1/4$ [Eqs. (2.3), (5.3a), and (5.3b)], requires substantially more computer time than what would be required for the separate solution of radionuclide concentration conditions, according to the numerical solution of (4) the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)], and (5) the computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)]. This is because the solution of the hydrodynamic conditions requires a substantially larger number of internal calculations [Eqs. (5.6)–(5.22)], with smaller computational time steps, according to the maximum allowable time step associated with the primary stability criterion for hydrodynamic conditions $\Delta t\{\overline{H},\overline{G}_x\}_1$ [Eq. (5.49)], and the solution of the radionuclide concentration conditions requires a substantially smaller number of internal calculations [Eqs. (2.5)–(2.12) and (2.17)–(2.21)], with larger computational time steps, according to the maximum allowable time step associated with the primary stability criterion for radionuclide concentration conditions $\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_1$ [Eq. (5.50)]. Therefore, for known hydrodynamic conditions in a river or an estuary, the application of the RADONE computer code, with the special option for excluding the computation of the hydrodynamic conditions by means of the auxiliary modular subroutine FLOWER

(Sects. 4.9, 5.2, and 6.17), which generates water surface elevations $\overline{H}_i$ and channel flow rates $\overline{G}_{x;i \pm \frac{1}{4}}$ in elements i and half-elements $i \pm \frac{1}{4}$, respectively, requires substantially less computer time than what would be required for the complete simultaneous solutions of both hydrodynamic conditions and radionuclide concentration conditions. Hence, in applying the RADONE computer code to the simulation of radionuclide concentration conditions in a river or an estuary, with known hydrodynamic conditions, it is substantially more cost-effective, because of computer time considerations, to utilize the special option for excluding the computation of the hydrodynamic conditions, by means of the auxiliary modular subroutine FLOWER (Sects. 4.9, 5.2, and 6.17), which generates water surface elevation and channel flow rate conditions based on specified input data.

However, the converse of this suggestion is not valid in applying the RADONE computer code to the simulation of only the hydrodynamic conditions in a river or an estuary. Because the computational algorithm of the RADONE computer code is based on the general concept of the UTA approach [e.g., Eraslan (1976), Eraslan and Witten (1984)], the structures of the different parts of the computational procedure required for the solution of the discrete-element equations of the mathematical system are similar and, in most cases, identical. Therefore, according to the general concept of UTA, the major computational parts of the numerical solution of the radionuclide concentration conditions, consisting of (1) the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)] and (2) the computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)] are automatically calculated during the numerical solution of the hydrodynamic conditions, consisting of (3) the computational subsystem of discrete-element equations for water surface elevation $\overline{H}_i$ in element i [Eqs. (2.1), (5.1a), and (5.1b)], (4) the computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i-\frac{1}{4}}$ in the upstream half-element [Eqs. (2.2), (5.2a), and (5.2b)], and (5) the computational subsystem of discrete-element equations for channel flow rate in downstream half-element $i + \frac{1}{4}$ [Eqs. (2.3), (5.3a), and (5.3b)]. The additional computer time required for the solution of the radionuclide concentration conditions during the solution of hydrodynamic conditions constitutes only a small portion of the overall computer time (generally less than 20%). Hence, in applying the RADONE computer code to the simulation of hydrodynamic conditions in a river or an estuary, it is extremely cost-effective to also include the simulation of the radionuclide concentration conditions, as needed, by obtaining simultaneous numerical solutions for the complete discretized mathematical system.

In applying the RADONE computer code to the simultaneous simulation of hydrodynamic and radionuclide concentration conditions in a typical controlled river or a tidal estuary with a generally small critical Froude number [e.g., Daily and Harleman (1966), Harleman (1966), Dronkers (1964)] conditions, $(Fr)_{cr} \ll 1$, the user must also consider the effects of the numerical dispersion [e.g., Roache (1972); Eraslan, Lin, and Sharp (1983)] that can be introduced in the solution of the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$, according to numerical solution of the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)]. For small critical Froude number conditions, $(Fr)_{cr} \ll 1$, the maximum allowable time step for numerical solution of hydrodynamic conditions, based on the primary stability criterion for hydrodynamic conditions $\Delta t\{\overline{H},\overline{G}_x\}_1$ [Eq. (5.49)], is much smaller than the maximum allowable time step for numerical solution of radionuclide concentration conditions, based on the primary stability criterion for radionuclide concentration conditions $\Delta t\{\overline{C}_{rw},\overline{C}_{rb}\}_1$ [Eq. (5.50)]. For this reason, the numerical solution of the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)] automatically uses an effective Courant number [e.g., Roache (1972); Eraslan, Lin, and Sharp (1983)] much smaller than 1. Considering the standard second-upwind-differencing forms (Sect. 3.3.2) used for the interpolation of the values of water concentration of the radionuclide in the water layer $\widetilde{C}_{rw;i\pm½}$, at the upstream and downstream enclosure surfaces at $i \pm ½$ of the elements, associated with longitudinal transport, the numerical solution of the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)], with the fourth-order Runge-Kutta-Gill method [e.g., Conte and deBoor (1972)], and with an effective Courant number [e.g., Roache (1972); Eraslan, Lin, and Sharp (1983)] much less than 1, can introduce the possible effect of appreciable numerical dispersion [e.g., Roache (1972); Eraslan (1974); Eraslan, Lin, and Sharp (1983)], based on mathematical analysis of the numerical stability characteristics of explicit, spatially discretized systems. The numerical dispersion effects that can be introduced in the solution of the water concentration of the radionuclide in the water layer $\overline{C}_{rw}$ can be eliminated (or minimized) by utilizing (1) the transportive-upwind-differencing technique [e.g., Eraslan, Lin, and Sharp (1983)] for the interpolation of the values of the water concentration of the radionuclide in the water layer $\widetilde{C}_{rw;i\pm½}$ at the upstream and downstream enclosure surfaces at $i \pm ½$ of the elements and (2) the composite time-splitting algorithm, [e.g., Eraslan, Lin, and Sharp (1983)] for the integration of the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i, which were developed for more-advanced, multidimensional, discrete-element mathematical models of the UTA project [Eraslan et al. (1976), Eraslan and Witten (1984)].

Hence, by considering the stability characteristics of the numerical solution of its complete system of discrete-element equations, the user can cost effectively apply the RADONE computer code to the simulation of hydrodynamic and radionuclide concentration conditions in a controlled river or a tidal estuary, based on numerically stable, convergent solutions of the fast-transient, one-dimensional, two-layer radionuclide transport model.

5.4 PARTIAL-DIFFERENTIAL-EQUATION SYSTEM EQUIVALENT TO CONTINUUM LIMIT OF DISCRETE-ELEMENT COMPUTATIONAL SYSTEM

The governing computational system of discrete-element equations of the fast-transient, one-dimensional, two-layer radionuclide transport model of the RADONE computer code, consisting of (1) the computational subsystem of discrete-element equations for water surface elevation $\overline{H}_i$ in element i [Eqs. (2.1), (5.1a), and (5.1b)], (2) the computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i-¼}$ in upstream half-element $i - ¼$ [Eqs. (2.2), (5.2a), and (5.2b)], (3) the computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i+¼}$ in downstream half-element $i + ¼$ [Eqs. (2.3), (5.3a), and (5.3b)], (4) the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)], and (5) the computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)], were all developed directly from the integral forms of the physical principles in one-dimensional, discretized forms, by utilizing the discrete-element method (DEM), and by considering one-dimensional segments of the main flow channel of a river or an estuary, and most importantly without considering any continuum limit partial differential equation. However, a governing system of partial differential equations, which is equivalent to the governing computational system of discrete-element equations [Eqs. (2.1)–(2.4), (2.16), and (5.1a)–(5.5b)], can be readily generated by considering the continuum limit ($\Delta x_i \rightarrow 0$) of the spatial dimensions (along the curvilinear longitudinal x-axis of the main flow channel) of the elements.

By considering the computational subsystem of discrete-element equations for water surface elevation $\overline{H}_i$ in element i [Eqs. (2.1), (5.1a), and (5.1b)], taking the continuum limit $(\Delta tx_i \rightarrow 0)$, and rearranging, an equivalent subsystem as a partial differential equation can be obtained for water surface elevation $H(t,x)$ as

$$B_{srf}\frac{\partial H}{\partial t} = -\frac{\partial G_x}{\partial x} + g_{rnf}(B_{srf} + a_{drn}) + g_{srm} + g_{grd} + g_{int} + g_{dis} \tag{5.58}$$

The continuum limit forms of definitions of the flow rates per unit length (along the curvilinear longitudinal x-axis of the main flow channel) consist of

1. flow rate per unit length, associated with streams and tributaries:

$$g_{srm} = \frac{\overline{G}_{srm}}{\Delta x} \quad , \tag{5.59a}$$

2. flow rate per unit length, associated with groundwater:

$$g_{grd} = \frac{\overline{G}_{grd}}{\Delta t} \quad , \tag{5.59b}$$

3. flow rate per unit length, associated with the intakes of power plants:

$$g_{int} = \frac{\overline{G}_{int}}{\Delta x} \quad , \text{ and} \tag{5.59c}$$

4. flow rate per unit length, associated with the discharges of power plants:

$$g_{dis} = \frac{\overline{G}_{dis}}{\Delta x} \quad ; \tag{5.59d}$$

and the continuum limit form of definition of the drainage area per unit length (along the curvilinear longitudinal x-axis of the main flow channel) becomes

$$a_{drn} = \frac{A_{drn}}{\Delta x} \quad . \tag{5.60}$$

Noting that the left-hand side of the partial differential equation for the water surface elevation $H(t,x)$ [Eq. (5.58)] also represents the time rate of change of the cross-section area A containing water in the main flow channel, that is

$$B_{srf}\frac{\partial H}{\partial t} = \frac{\partial A}{\partial t} \quad , \tag{5.61}$$

the partial differential equation for conservation of water mass in the main flow channel that is equivalent to the computational subsystem of discrete-element equations for water surface elevation $\overline{H}_i$ in element i [Eqs. (2.1), (5.1a), and (5.1b)] can be rearranged as

$$\frac{\partial A}{\partial t} + \frac{\partial G_x}{\partial x} = g_{rnf}(B_{srf} + a_{drn}) + g_{srm} + g_{grd} + g_{int} + g_{dis} \tag{5.62}$$

By considering the computational subsystem for the channel flow rate, consisting of (1) the computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i-1/4}$ in upstream half-element $i - 1/4$ [Eqs. (2.2), (5.2a), and (5.2b)] and (2) the computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i+1/4}$ in downstream half-element $i + 1/4$ [Eqs. (2.3), (5.3a), and (5.3b)], taking the continuum limit ($\Delta x_i \rightarrow 0$), and rearranging, an equivalent subsystem as a partial differential equation for momentum along the curvilinear longitudinal *x*-axis of the main flow channel can be obtained for the flow rate as

$$\frac{\partial G_x}{\partial t} + \frac{\partial}{\partial x}(G_x V_x) = -g_a A \frac{\partial H}{\partial x} + g_a A \Omega_x + \frac{\partial \overline{G}_x^{*\prime}}{\partial x} + \tilde{f}'_{x,bot}$$

$$+ B_{srf}\left[g_{rnf}\left(V_{x,rnf} + \frac{a_{drn}}{B_{srf}} V_{x,drn}\right) + \tilde{f}'_{x,srf}\right]$$

$$+ g_{srm} V_{x,srm} + g_{grd} V_{x,grd} + g_{int} V_{x,int} + g_{dis} V_{x,dis} \tag{5.63}$$

By considering the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)], taking the continuum limit ($\Delta x_i \rightarrow 0$), and rearranging, an equivalent subsystem as a partial differential equation can be obtained for water concentration of the radionuclide in the water layer $C_{rw}(t,x)$ as

$$A \frac{\partial C_{rw}}{\partial t} = A \dot{C}_{rw} - \frac{\partial}{\partial x}(G_x C_{rw}) + C_{rw} \frac{\partial G_x}{\partial x} + \frac{\partial G_{rw}}{\partial x}$$

$$+ g_{grd,wl}(C_{rw,grd,wl} - C_{rw}) + g_{rw,bot}$$

$$+ B_{srf} g_{rnf}\left[(C_{rw,rnf} - C_{rw}) + \frac{a_{drn}}{B_{srf}}(C_{rw,drn} - C_{rw})\right]$$

$$+ g_{srm,wl}(C_{rw,srm,wl} - C_{rw}) + g_{int,wl}(C_{rw,int,wl} - C_{rw}) + g_{dis,wl}(C_{rw,dis,wl} - C_{rw}) \ . \tag{5.64}$$

Again, the continuum limit forms of definitions of the flow rates per unit length (along the curvilinear longitudinal *x*-axis of the main flow channel) into the water layer (denoted by subscript *wl*) consist of

1. flow rate per unit length into the water layer (*wl*), associated with groundwater:

$$g_{grd,wl} = \frac{\overline{G}_{grd,wl}}{\Delta x} \ , \tag{5.65a}$$

2. flow rate per unit length into the water layer (*wl*), associated with streams and tributaries:

$$g_{srm,wl} = \frac{\overline{G}_{srm,wl}}{\Delta x} \ , \tag{5.65b}$$

3. flow rate per unit length into the water layer (*wl*), associated with the intakes of power plants:

$$g_{int,wl} = \frac{\overline{G}_{int,wl}}{\Delta x} \quad , \text{ and} \tag{5.65c}$$

4. flow rate per unit length into the water layer (*wl*), associated with the discharges of power plants:

$$g_{dis,wl} = \frac{\overline{G}_{dis,wl}}{\Delta x} \quad ; \tag{5.65d}$$

and the continuum limit form of definition of the bottom radionuclide transport rate per unit length, associated with the water layer (*wl*), becomes

$$g_{rw,bot} = \frac{\overline{G}_{rw,bot}}{\Delta x} \quad . \tag{5.66}$$

Noting that the left-hand side of the partial differential equation for water concentration of the radionuclide in the water layer $C_{rw}(t,x)$ [Eq. (5.64)] can be formulated as

$$A\frac{\partial C_{rw}}{\partial t} = \frac{\partial}{\partial t}(AC_{rw}) - C_{rw}\frac{\partial A}{\partial t} \quad , \tag{5.67}$$

and rearranging the terms, it can be reformulated as

$$\begin{aligned}\frac{\partial}{\partial t}(AC_{rw}) + \frac{\partial}{\partial x}(G_x C_{rw}) = A\dot{C}_{rw} + \frac{\partial G_{rw,x}}{\partial x} \\ + g_{grd,wl}C_{rw,grd,wl} + g_{rw,bot} + g_{rnf}(B_{srf}C_{rw,rnf} + a_{drn}C_{rw,drn}) \\ + g_{srm,wl}C_{rw,srm,wl} + g_{int,wl}C_{rw,int,wl} + g_{dis,wl}C_{rw,dis,wl} \\ + C_{rw}\left[\frac{\partial A}{\partial t} + \frac{\partial G_x}{\partial x} - g_{grd,wl} - g_{rnf}(B_{srf} + a_{drn}) - g_{srm,wl} - g_{int,wl} - g_{dis,wl}\right] \quad .\end{aligned} \tag{5.68}$$

According to the formulation of the specified transport conditions (Sect. 4) for the two layers of the fast-transient, one-dimensional, two-layer radionuclide transport model of the RADONE computer code, the net flow rate per unit length into the main flow channel consists of the sum of (1) the flow rate per unit length into the water layer (*wl*) and (2) the flow rate per unit length into the bottom layer (*bl*); hence,

$$g_{grd} = g_{grd,wl} + g_{grd,bl} \quad , \text{ or } \quad g_{grd,wl} = g_{grd} - g_{grd,bl} \quad , \tag{5.69a}$$

$$g_{srm} = g_{srm,wl} + g_{srm,bl} \quad , \text{ or } \quad g_{srm,wl} = g_{srm} - g_{srm,bl} \quad , \tag{5.69b}$$

$$g_{int} = g_{int,wl} + g_{int,bl} \quad , \text{ or } \quad g_{int,wl} = g_{int} - g_{int,bl} \quad , \tag{5.69c}$$

$$g_{dis} = g_{dis,wl} + g_{dis,bl} \quad , \text{ or } \quad g_{dis,wl} = g_{dis} - g_{dis,bl} \quad , \tag{5.69d}$$

where again the continuum limit forms of the flow rates per unit length (along the curvilinear longitudinal x-axis of the main flow channel) into the bottom layer (bl) consist of

1. flow rate per unit length into the bottom layer (bl), associated with groundwater:

$$g_{grd,bl} = \frac{\overline{G}_{grd,bl}}{\Delta x} \ , \tag{5.70a}$$

2. flow rate per unit length into the bottom layer (bl), associated with streams and tributaries:

$$g_{srm,bl} = \frac{\overline{G}_{srm,bl}}{\Delta x} \ , \tag{5.70b}$$

3. flow rate per unit length into the bottom layer (bl), associated with the intakes of power plants:

$$g_{int,bl} = \frac{\overline{G}_{int,bl}}{\Delta x} \ , \text{ and} \tag{5.70c}$$

4. flow rate per unit length into the bottom layer (bl), associated with the discharges of power plants:

$$g_{dis,bl} = \frac{\overline{G}_{dis,bl}}{\Delta x} \ . \tag{5.70d}$$

Substituting the definitions of the flow rates per unit length [Eqs. (5.65a)–(5.65d) and (5.69a)–(5.70d)] into the partial differential equation for water concentration of the radionuclide in the water layer $C_{rw}(t,x)$ [Eq. (5.68)] and rearranging,

$$\begin{aligned}
\frac{\partial}{\partial t}(AC_{rw}) + \frac{\partial}{\partial x}(G_x C_{rw}) = A\hat{C}_{rw} + \frac{\partial G_{rw,x}}{\partial x} \\
+ g_{grd,wl}C_{rw,grd,wl} + g_{rw,bot} + g_{rnf}(B_{srf}C_{rw,rnf} + a_{drn}C_{rw,drn}) \\
+ g_{srm}C_{rw,srm,wl} + g_{int,wl}C_{rw,int,wl} + g_{dis,wl}C_{rw,dis,wl} \\
+ C_{rw}\Bigg[\frac{\partial A}{\partial t} + \frac{\partial G_x}{\partial t} - g_{grd} - g_{rnf}(B_{srf} + a_{drn}) \\
- g_{srm} - g_{int} - g_{dis} + (g_{grd,bl} + g_{srm,bl} + g_{int,bl} + g_{dis,bl})\Bigg] \ .
\end{aligned} \tag{5.71}$$

The last bracketed term on the right-hand side of the partial differential equation for water concentration of the radionuclide in the water layer $C_{rw}(t,x)$ [Eq. (5.71)], which multiplies C_{rw}, is approximately equal to zero for two reasons. The first part of the term is identically equal to zero since it is the final form of the partial differential equation for conservation of water mass in the main flow channel [Eq. (5.62)]. The second part of the term, consisting of the sum of the specified flow rates per unit length into the bottom layer (*bl*) in a sense represents the conservation of water mass in the bottom layer (*bl*), which can be formulated as

$$\frac{\partial}{\partial t}(\Gamma D_{bl}) = g_{grd,bl} + g_{srm,bl} + g_{int,bl} + g_{dis,bl} \ . \tag{5.72}$$

According to the formulation of the bottom radionuclide transport submodel (Sect. 3.5), it is assumed that the convective transport of the radionuclide between the water layer and the bottom layer is negligible. Furthermore, the formulation of the computational subsystem of discrete-element equations for the bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element *i* [Eqs. (2.16), (5.5a), and (5.5b)] assumes that the depth of the bottom layer D_{bl} remains as a specified constant, which does not vary temporally or spatially in the main flow channel. Hence, the formulation of the radionuclide transport conditions for the bottom layer (*bl*) assumes that the convective radionuclide transport that results from the net sum of the specified flow rates per unit length into the bottom layer is negligible; therefore,

$$\frac{\partial}{\partial g}(\Gamma D_{bl}) = g_{grd,bl} + g_{srm,bl} + g_{int,bl} + g_{dis,bl} \simeq 0 \ . \tag{5.73}$$

It is important to point out that this assumption is a reasonable approximation, since the depth of the bottom layer D_{bl} is generally much smaller than the total depth $\overline{D}$ of the main flow channel; hence, the fractions of the specified flow rates into the water layer (*wl*) are generally much more than the fractions of the specified flow rates into the bottom layer (*bl*) of the main flow channel (Sect. 4). For special cases, when in implementing the RADONE computer code for the simulation of the radionuclide concentration conditions, it becomes necessary to consider substantial fractions of specified flow rates into the bottom layer, the bottom radionuclide transport submodel (Sect. 3.5) can be readily modified to include the effect of the convective radionuclide transport rate between the bottom layer and the water layer, which results as the consequence of the net, nonnegligible, flow rate, between the bottom layer and the water layer, generated by the cumulative effect of all the specified flow rates into the bottom layer (*bl*) [Sect. 4 and Eq. (5.73)] of the main flow channel.

Hence, considering the fact that the last bracketed term on the right-hand side of the partial differential equation for water concentration of the radionuclide in the water layer $C_{rw}(t,x)$ [Eq. (5.71)] can be formulated as zero, the conventional, conservative form of the partial differential equation representing the pseudoconservation principle for the radionuclide in the water layer becomes

$$\begin{aligned} \frac{\partial}{\partial t}(AC_{rw}) + \frac{\partial}{\partial x}(G_x C_{rw}) &= A\dot{C}_{rw} + \frac{\partial G_{rw,x}}{\partial x} \\ &+ g_{grd,wl}C_{rw,grd,wl} + g_{rw,bot} + g_{rnf}(B_{srf}C_{rw,rnf} + a_{drn}C_{rw,drn}) \\ &+ g_{srm}C_{rw,srm,wl} + g_{int,wl}C_{rw,int,wl} + g_{dis,wl}C_{rw,dis,wl} \end{aligned} \tag{5.74}$$

By considering the computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element *i* [Eqs. (2.4), (5.4a), and (5.4b)], taking the continuum limit ($\Delta x_i \rightarrow 0$), and rearranging, an equivalent subsystem as a partial differential equation can be obtained for bottom concentration of the radionuclide in the bottom layer $C_{rb}(t,x)$ as

$$(\Gamma D_{bl})\frac{\partial C_{rb}}{\partial t} = (\Gamma D_{bl})\dot{C}_{rb} + g_{grd,bl}(C_{rb,grd,bl} - C_{rb})$$

$$+ g_{rb,bot} + g_{srm,bl}(C_{rb,srm,bl} - C_{rb})$$

$$+ g_{int,bl}(C_{rb,int,bl} - C_{rb}) + g_{dis,bl}(C_{rb,dis,bl} - C_{rb}) \ , \qquad (5.75)$$

where the continuum limit forms of the flow rates per unit length (along the curvilinear longitudinal x-axis of the main flow channel) into the bottom layer were already defined [Eqs. (570a)–(5.70d)].

The partial differential equation for bottom concentration of the radionuclide in the bottom layer $C_{rb}(t,x)$ [Eq. (5.75)] can be rearranged as

$$\frac{\partial}{\partial t}[(\Gamma D_{bl})C_{rb}] = (\Gamma D_{bl})\dot{C}_{rb} + g_{grd,bl}C_{rb,grd,bl} + g_{rb,bot}$$

$$+ g_{srm,bl}C_{rb,srm,bl} + g_{int,bl}C_{rb,int,bl} + g_{dis,bl}C_{rb,dis,bl}$$

$$+ C_{rb}\left[\frac{\partial}{\partial t}(\Gamma D_{bl}) - g_{grd,bl} - g_{srm,bl} - g_{int,bl} - g_{dis,bl}\right] \qquad (5.76)$$

The last bracketed term on the right-hand side of the partial differential equation for bottom concentration of the radionuclide in the bottom layer $C_{rb}(t,x)$ [Eq. (5.75)] is identically equal to zero since it represents the conservation of water mass in the bottom layer (bl). Hence, the final partial differential equation representing the pseudo conservation principle for the radionuclide in the bottom layer becomes

$$\frac{\partial}{\partial t}[(\Gamma D_{bl})C_{rb}] = (\Gamma D_{bl})\dot{C}_{rb} + g_{grd,bl}C_{rb,grd,bl} + g_{rb,bot}$$

$$+ g_{srm,bl}C_{rb,srm,bl} + g_{int,bl}C_{rb,int,bl} + g_{dis,bl}C_{rb,dis,bl} \ . \qquad (5.77)$$

Hence, it can be concluded that the computational system of discrete-element equations, consisting of (1) the computational subsystem of discrete-element equations for water surface elevation $\overline{H}_i$ in element i [Eqs. (2.1), (5.1a), and (5.1b)], (2) the computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i-\frac{1}{4}}$ in upstream half-element i − ¼ [Eqs. (2.2), (5.2a), and (5.2b)], (3) the computational subsystem of discrete-element equations for channel flow rate $\overline{G}_{x;i+\frac{1}{4}}$ in downstream half-element i + ¼ [Eqs. (2.3), (5.3a), and (5.3b)], (4) the computational subsystem of discrete-element equations for water concentration of the radionuclide in the water layer $\overline{C}_{rw;i}$ in element i [Eqs. (2.4), (5.4a), and (5.4b)], and (5) the computational subsystem of discrete-element equations for bottom concentration of the radionuclide in the bottom layer $\overline{C}_{rb;i}$ in element i [Eqs. (2.16), (5.5a), and (5.5b)], approximately represents, in the continuum limit ($\Delta x_i \rightarrow 0$), an equivalent, conventional, generally conservative form of a partial differential equation system, consisting of (1) the partial differential equation, representing the conservation principle for the water mass in the main flow channel, for water surface elevation $H(t,x)$ [Eq. (5.62)], (2) the partial differential equation, representing the momentum principle, for the channel flow rate (along the curvilinear longitudinal x-axis of the main flow channel) $G_x(t,x)$ [Eq. (5.63)], (3) the partial differential equation, representing the pseudoconservation principle for the radionuclide in the water layer, for the water concentration of the radionuclide in the water layer $C_{rw}(t,x)$ [Eq. (5.74)], and (4) the partial differential equation, representing the pseudoconservation principle for the radionuclide in the bottom layer, for the bottom concentration of the radionuclide in the bottom layer $C_{rb}(t,x)$ [Eq. (5.77)].

6. PROGRAM STRUCTURE OF THE RADONE COMPUTER CODE

The RADONE computer code was developed specifically as a general-usage computer program that can be used readily by the staff of the U.S. Nuclear Regulatory Commission (NRC); the U.S. Department of Energy (DOE); the U.S. Environmental Protection Agency (EPA); the U.S. Department of the Interior; the U.S. Department of the Army, Corps of Engineers; the Tennessee Valley Authority; other federal and state regulatory agencies; and the nuclear electric power generating utility companies that are responsible for the assessment of the radiological impact of accidental radiological releases into the aquatic flow regions of rivers and estuaries.

RADONE was programmed in FORTRAN to be compatible with the in-house computer systems of NRC and the computer systems of DOE's national laboratories and other federal agencies. The computer program was developed primarily to run on Digital Equipment Corporation (DEC), IBM, and PRIME computer systems. However, with minor modifications of the FORTRAN statements associated with the input/output (I/O) formats, it can be installed in any large or medium-size computer system, including Control Data Corporation (CDC), Hewlett Packard (HP), APOLLO, and other equipment with comparable central processing unit (CPU) capabilities.

6.1 GENERAL DISCUSSION OF THE PROGRAM STRUCTURE

According to the fundamental concept of Unified Transport Approach (UTA), the computational structure of RADONE, in general, is similar to the computational structure of ESTONE [Eraslan (1983)], which represents the fundamental computational algorithm of all the fast-transient (tidal-transient), one-dimensional, discrete-element transport models for controlled rivers and tidal estuaries [Eraslan and Witten (1984)]. Hence, in the discussions of the program structure of RADONE, the sections of the text, either describing the operational features of the computer code or presenting instructions for the preparation of the specified input data, which are similar or identical to corresponding sections in ESTONE [Eraslan (1983)], are not repeated, but presented only as summaries; and the user is referred to the users manual of ESTONE, which contains all the detailed information about the common parts of the computational structures of the two computer codes. However, it is important to point out that the sections of the report that are presented as summaries are organized to guarantee the inclusion of all the instructional information that is required for the implementation of the RADONE computer code in the analysis of site-specific problems.

The version of RADONE presented in this report can be classified as a "development program," which is based on the computationally optimized mathematical solution algorithm associated with the fast-transient, one-dimensional, discrete-element radionuclide transport model (Sects. 2–5). However, it cannot be classified as a "production program" because it does not include the optimization (from FORTRAN programming structure considerations) necessary to minimize (1) the computer run times [CPU time and I/O time] and (2) computer storage requirements for repetitive production-type applications to a particular site-specific problem.

The program structure of the development program version of RADONE consists of a MAIN program and 13 modular subroutines: REGION, INITAL, SOLVER, ENDCON, CONVEC, TURBUL, GROUND, SURFAC, STREAM, PLANTS, BOTTOM, RADIOR, and OUTPUT (Fig. 6.1). Two additional auxiliary subroutines, FLOWER and STORER, are also included according to the user-specified option for excluding the solution of the hydrodynamic conditions by incorporating the already computed and stored results of flow conditions as input data (Fig. 6.1).

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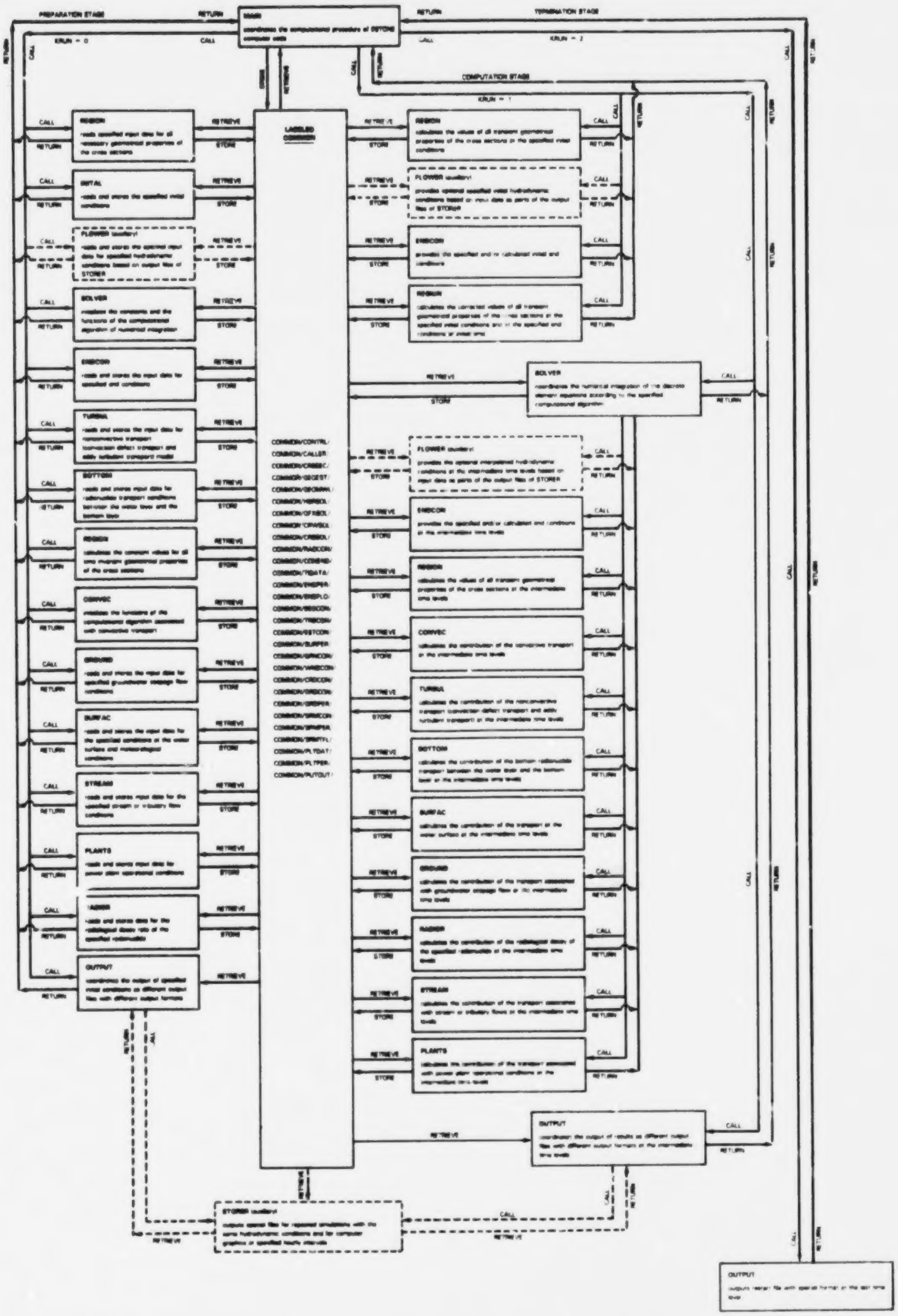
PREPARATION STAGE
RETURN
CALL
KRUN = 0
TERMINATION STAGE
KRUN = 2
COMPUTATION STAGE
KRUN = 1
LABELED COMMON
REGION
INITAL
FLOWER (auxiliary)
SOLVER
SNBCON
TURBUL
BOTTOM
CONVEC
GROUND
SURFAC
STREAM
PLANTS
OUTPUT
STORER (auxiliary)
RETRIEVE
STORE

Fig. 6.1. Modular structure of the "advanced development program" version of the RADONE computer code.

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The MAIN program controls the overall computational procedure of RADONE (Fig. 6.1) by using the 14 subroutines for (1) incorporating the specified input data (Sects. 3, 4, 5, and 7), (2) solving the governing set of discrete-element equations of the radionuclide transport model (Sects. 2–5), and (3) presenting and/or storing the output of the computational results. The individual structures and the computational procedures of the MAIN program and the 14 subroutines will be presented in summary form in Sects. 6.2 through 6.17.

The MAIN program and the 14 subroutines are combined to form the unified structure and the overall computational procedure of RADONE by special sets of FORTRAN variables that are common to more than 1 subroutine. These special sets of FORTRAN variables, which, in general, correspond to the important mathematical variables of the governing discrete-element equations, are included in the labeled COMMON statements of the subroutines that use them in their individual internal computational procedures. The name of each labeled COMMON statement and the name of each FORTRAN variable in these special sets of FORTRAN variables of the RADONE computer code were selected carefully to enable the user to readily associate each FORTRAN variable with its corresponding mathematical form in the discrete-element formulation of the transport model (Sects. 2–5). It is important to point out that, in general, during the overall computational procedure of RADONE, computational operations that include the values of the FORTRAN variables passed through allocated common storage areas between different modular subroutines require more CPU time for the labeled COMMON statements than for the unlabeled COMMON statements. The labeled COMMON statements are only used in the development program version of RADONE to aid the user in understanding the structures and operational procedures of the overall computer program and its different modular subroutines.

Each modular subroutine that requires input data for calculating a certain computational part associated with a particular type of transport phenomenon is structured to read the complete set of its required specified input data within the subroutine. Hence, consistent with the fundamental computational concept of UTA [Eraslan et al. (1977), Eraslan and Witten (1984)], each set of required specified input data for each modular subroutine can be prepared or modified without affecting the sets of required specified input data for the MAIN program and the other modular subroutines. Furthermore, again consistent with the fundamental computational concept of UTA [Eraslan et al. (1977), Eraslan and Witten (1984)], the sets of required specified input data to the modular subroutines of RADONE, which are common to the other fast-transient, one-dimensional, discrete-element mathematical transport models, are formulated according to identical, common data formats, which can be used directly as the sets of required specified input data to the modular subroutines of the other seven computer codes of the UTA project [Eraslan et al. (1977), Eraslan and Witten (1984)].

All modular subroutines of the development program version of RADONE are structured according to a systematic arrangement of FORTRAN statement numbers. The FORTRAN statement numbers between 1000 and 1999 are allocated for reading and writing sets of specified input data in all the modular subroutines. The numbers between 2000 and 2999 are allocated for the computational procedure of the modular subroutine. The numbers between 4000 and 6999 are generally allocated for (1) use of the different options (if any) of the computational procedure of the modular subroutine and/or (2) inclusion of the different individual subgroups of the transported quantity (e.g., concentrations of different sediment classes, chemical species, and different biological group populations). The FORTRAN statement numbers between 3000 and 3999 are generally allocated for writing special data sets that are required as the initial specified input data for restarting the computations at any specified time. Again consistent with the fundamental computational concept of UTA [Eraslan et al. (1977), Eraslan and Witten (1984)], all the modular subroutines of the development program versions of the other seven computer codes associated with the fast-transient, one-dimensional, discrete-element mathematical transport models are structured according to the identical systematic arrangement of the FORTRAN statement numbers.

The development program version of RADONE was specifically programmed to enable the user to implement the FORTRAN program with a reasonable level of understanding of the computational features of the fast-transient, one-dimensional, discrete-element mathematical transport model for simulating hydrodynamic and radionuclide concentration conditions in a controlled river or a tidal estuary (Sects. 2–5). Hence, all the names of the important FORTRAN variables were selected carefully to enable the user to readily associate them with their corresponding mathematical variables in the discrete-element formulation of the mathematical model (Sects. 2–5). Furthermore, consistent with the fundamental computational concept of UTA [Eraslan et al. (1977), Eraslan and Witten (1984)], the names of the FORTRAN variables that correspond to the mathematical variables that are common in the discrete-element formulations of the seven other fast-transient, one-dimensional, discrete-element mathematical transport models were used identically in RADONE and the other seven computer codes.

6.2 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MAIN PROGRAM

The MAIN program controls the complete computational procedure of the RADONE computer code in three operational stages: preparation, computation, and termination.

The preparation stage coordinates the preparation of all the modular subroutines for the subsequent computations by (1) reading the required sets of specified input data in each subroutine and/or (2) initializing the values of various coefficients, parameters, and variables in each subroutine, based on user-specified options.

The computation stage coordinates (1) the main computational procedures associated with the numerical integration (solution) of the governing system of discrete-element equations by the modular subroutines at each specified intermediate time step and (2) the output of the computed results and the representative norms of the truncation errors of the numerical integration (solution) at the end of each specified intermediate time step.

The termination stage coordinates the output of the special data sets, based on the computed results of the numerical integration (solution) at the end of the last specified time step, which are required as the specified initial conditions for restarting the subsequent computations as needed.

The MAIN program does not include any part of the computational algorithm of RADONE associated with the numerical integration (solution) of the governing set of discrete-element equations of the fast-transient, one-dimensional, radionuclide transport model (Sect. 5).

The abbreviated flow chart of the structure and computational procedure of the MAIN program is presented in Figs. 6.2a and 6.2b. The MAIN program coordinates the three operational stages by using the principal integer control parameter KRUN, which is included in the labeled COMMON/CONTRL/ statement in all the modular subroutines of RADONE.

6.2.1 Preparation Stage

The MAIN program assigns the value of the integer control parameter KRUN = 0 (Fig. 6.2a), which indicates that the MAIN program and all the modular subroutines of RADONE will be concerned only with (1) the reading of the required sets of specified input data and/or (2) the initialization of the values of various coefficients, parameters, and variables, based on user-specified options as specified input data for the

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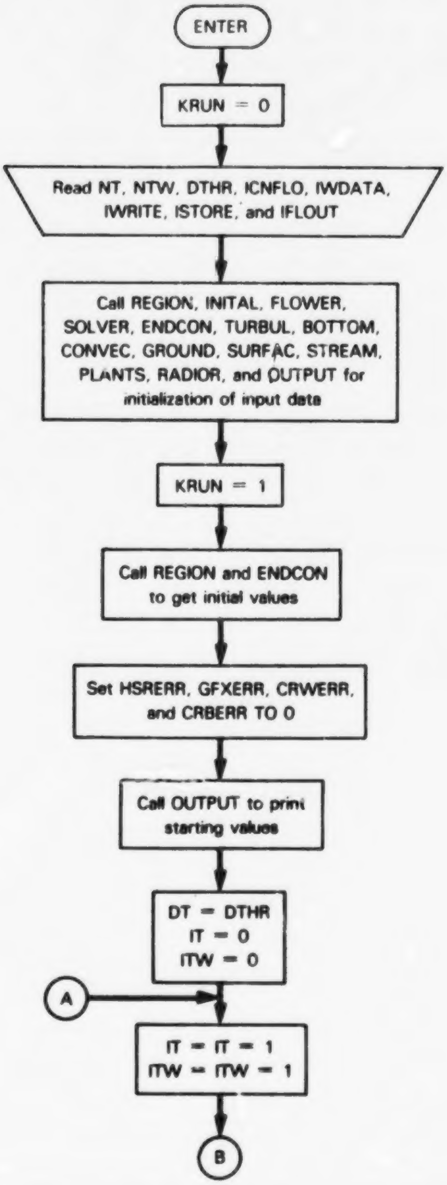
ENTER
KRUN = 0
Read NT, NTW, DTHR, ICNFLO, IWDATA, IWRITE, ISTORE, and IFLOUT
Call REGION, INITAL, FLOWER, SOLVER, ENDCON, TURBUL, BOTTOM, CONVEC, GROUND, SURFAC, STREAM, PLANTS, RADIOR, and OUTPUT for initialization of input data
KRUN = 1
Call REGION and ENDCON to get initial values
Set HSRERR, GFXERR, CRWERR, and CRBERR TO 0
Call OUTPUT to print starting values
DT = DTHR
IT = 0
ITW = 0
A
IT = IT = 1
ITW = ITW = 1
B

Fig. 6.2a. Abbreviated flowchart of the structure and computational procedure of the MAIN program of the RADONE computer code.

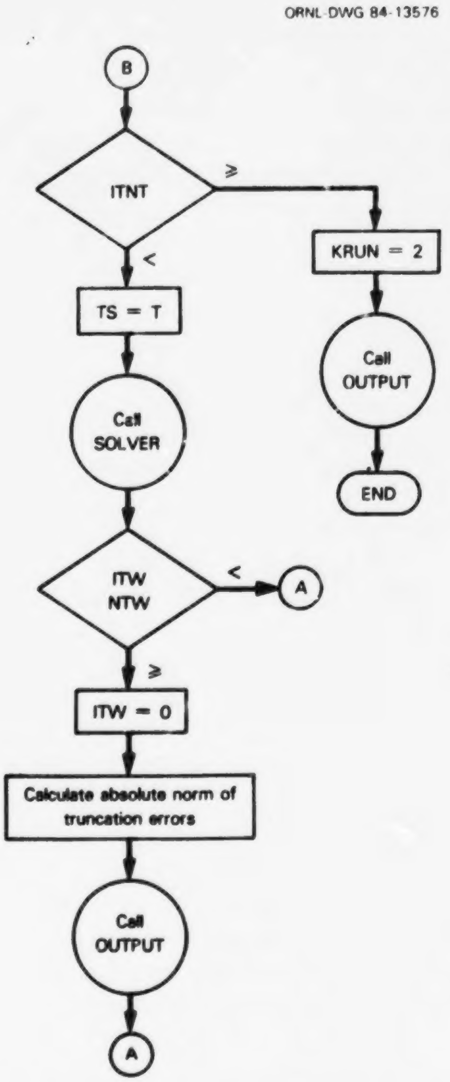
ORNL-DWG 84-13576
B
ITNT
≥
<
KRUN = 2
TS = T
Call
OUTPUT
END
Call
SOLVER
ITW
NTW
<
A
≥
ITW = 0
Calculate absolute norm of
truncation errors
Call
OUTPUT
A

Fig. 6.2b. Abbreviated flowchart of the structure and computational procedure of the MAIN program of the RADONE computer code (continued).

values of the various integer control parameters (Sect. 7.2). The preparation stage is completed according to the following two operational steps (Fig. 6.2a):

1. The MAIN program reads the set of specified input data (Sect. 7.2) for the values of the parameters that control the computational procedure of RADONE. The set of specified input data include (a) the parameters for the temporal numerical integration (solution) of the governing system of discrete-element equations (Sect. 5) and (b) the integer control parameters for the user-specified forms of the output, representing the computer simulation results of RADONE computer code.

2. The MAIN program calls the modular subroutines in the order of REGION, INITAL, FLOWER (if ICNFLO < 1, indicating that input data would be required for hydrodynamic conditions), SOLVER, ENDCON, TURBUL, BOTTOM, REGION, CONVEC, GROUND, SURFAC, STREAM, PLANTS, and OUTPUT. Each subroutine with the integer control parameter KRUN = 0 through the labeled COMMON/CONTRL/ reads the required sets of specified input data for the subroutine and/or initializes the values of all the coefficients, parameters, and variables in each subroutine based on user-specified options.

At the end of the preparation stage, the MAIN program completes all the necessary initialization procedures that would be required before proceeding with the subsequent computational procedures.

6.2.2 Computation Stage

The MAIN program reassigns the value of the integer control parameter as KRUN = 1 (Fig. 6.2a), which indicates that the MAIN program and all the modular subroutines of RADONE would be computing the different parts of the general computational algorithm associated with the numerical integration (solution) of the governing system of discrete-element equations of the transport model (Sect. 5). The computation stage is completed according to the following five operational steps (Figs. 6.2a and 6.2b):

1. The MAIN program calls the modular subroutine REGION, which calculates the geometric characteristics of the cross-sectional areas of the main flow channel (Sect. 3), including the two cross-sectional areas at the upstream and downstream ends of the curvilinear longitudinal span of the main flow channel, based on specified input data for the initial conditions of water surface elevations in the elements. The MAIN program then calls the modular subroutine ENDCON, which calculates the upstream- and downstream-end conditions based on (a) specified input data for the temporal variations of upstream and downstream-end conditions (Sect. 4.3) and (b) conditions in the elements, according to specified input data for initial conditions. The MAIN program again calls REGION, which recalculates the geometric characteristics of the cross-sectional areas of the main flow channel, including the two upstream- and downstream-end cross-sectional areas, with already corrected water surface elevation values from the subroutine ENDCON, based on specified input data for the temporal variations of upstream- and downstream-end water surface elevation conditions.
2. The MAIN program initializes to zero all values of the absolute norms of truncation errors, defined as the sums of the absolute values of truncation errors in all the elements, for all principal solution variables of the solution. These variables are the absolute norms of the truncation errors for (a) water surface elevation HSRERR, (b) channel flow rate GFXERR, (c) water concentration of the radionuclide in the water layer CRWERR, and (d) bottom concentration of the radionuclide in the bottom layer CRBERR, in all the NX elements of the main flow channel.
3. The MAIN program calls the modular subroutine OUTPUT, which writes the initial conditions for the solution variables (a) water surface elevation HSR(IX), (b) channel flow rate GFX(IX), (c) water concentration of the radionuclide in the water layer CRW(IX), and (d) bottom concentration of the radionuclide in the bottom layer, in all the NX elements of the main flow channel.
4. The MAIN program initiates and completes the fundamental computational procedure associated with the numerical integration (solution) of the governing system of discrete-element equations (Sect. 5) for the specified total duration of the computer simulations, according to NT as the specified total number of time steps Δt_{RKG} and DTHR (in hours) as the specified time step Δt_{RKG} of the Runge-Kutta-Gill method [e.g., Conte and deBoor (1972)]. The MAIN program advances the time T (in hours) NT

times by calling the modular subroutine SOLVER (Fig. 6.2b), which numerically integrates, according to the Runge-Kutta-Gill method [e.g., Conte and deBoor (1972)], the governing system of $5N$ discrete-element equations (Sect. 5) to obtain the solution at the advanced time level T + DTHR, in terms of the solution at the previous time level T, for the $5N$ number of principal flow variables of the solution (Sect. 5). These variables are (a) water surface elevation HSR(IX) in the element IX, (b) channel flow rate GFX(IMX) in the upstream half-element IMX, (c) channel flow rate GFX(IPX) in the downstream half-element IPX, (d) water concentration of the radionuclide in the water layer CRW(IX) in the element IX, and (e) bottom concentration of the radionuclide in the bottom layer CRB(IX) in the element IX, for all NX elements (Appendix A). After every NTW time step, the MAIN program calculates the new values of the absolute norms of the truncation errors (Fig. 6.2b). The values are the absolute norms of the truncation errors for (a) water surface elevation HSRERR, (b) channel flow rate GFXERR, (c) water concentration of the radionuclide in the water layer CRWERR, and (d) bottom concentration of the radionuclide in the bottom layer CRBERR. Finally, after every NTW time step, the MAIN program calls the modular subroutine OUTPUT (Fig. 6.2b), which writes in different output formats (according to specified input data for the values of the integer control parameters, as user-specified options IWRITE and IWSTORE) the computed results of (a) the principal solution variables of the solution in all NX elements and (b) the absolute norms of the truncation errors.

At the end of the computation stage, the MAIN program completes (a) the fundamental computational procedure associated with the numerical integration (solution) and (b) the output of the computed results for the principal solution variables, for the specified total duration of the computer simulations.

6.2.3 Termination Stage

The MAIN program reassigns the value of the integer control parameter as KRUN = 2 (Fig. 6.2b), which indicates that all computational procedures associated with the computer simulations have been completed. The MAIN program then calls the modular subroutine OUTPUT, when the value KRUN = 2, which is passed through the labeled COMMON/CONTRL/, writes on a separate restart data file, according to a special format, the time T (in hours) and the computed results at the last time level of the computer simulations for the principal flow variables of the solution. These variables are (a) water surface elevation HSR(IX) in the element IX, (b) channel flow rate GFX(IMX) in the upstream half-element IMX, (c) channel flow rate GFX(IPX) in the downstream half-element IPX, (d) water concentration of the radionuclide in the water layer CRW(IX) in the element IX, and (e) bottom concentration of the radionuclide in the bottom layer CRB(IX) in the element IX, for all the NX elements of the main flow channel. After the modular subroutine OUTPUT completes the writing of the restart file, which corresponds identically to the required set of data for the specified initial conditions for subsequent simulations, the MAIN program terminates (Fig. 6.2b) the computational procedure of RADONE.

6.3 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE REGION

The modular subroutine REGION calculates all the necessary geometric properties (Sects. 2 and 3) of the cross sections of the main flow channel. The specified input data can incorporate simple and/or detailed geometric data about the cross-sectional contours of the main flow channel at different locations along the curvilinear longitudinal x-axis of the main flow channel. These data can vary in accuracy from estimated,

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approximate, rectangular, or triangular cross-sectional profiles to available detailed information on U.S. coastal and geodetic survey charts, which can be obtained for all major navigable rivers and estuaries (Sect. 4.2).

The computational structure of the modular subroutine REGION is identical in both the RADONE and the ESTONE computer codes [Eraslan (1983)]. Therefore, the structure and computational procedure of the modular subroutine REGION will be presented only in summary form, since the user can readily obtain the detailed information, if necessary, from the users manual of the ESTONE computer code [Eraslan (1983), Sect. 6.3].

The computational algorithm associated the the fast-transient, one-dimensional, discrete-element radionuclide transport model can realistically simulate rapid variations of water depth in the main flow channel. These variations can occur under such conditions as floods caused by excess storm drainage or by dam failure. Hence, the general computational procedure of REGION uses a trapezoidal integration technique to calculate at every time level of the numerical solution the required geometric properties of a cross section by integrating from the bottom of the main flow channel at maximum depth to the level of the water surface elevation HSR (Appendix A) at the location of the cross section. Therefore, the computational algorithm of the modular subroutine REGION includes all the necessary capabilities for realistically simulating the hydrodynamic conditions in a controlled river or a tidal estuary under catastrophic hydrological accident conditions, which can conceivably lead to catastrophic accidental radionuclide release scenarios into the water body.

The structure and computational procedure of REGION (Figs. 6.3a–6.3e) consist of two operational stages, the preparation stage and the computation stage, which are initiated and completed, depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.3.1 Preparation Stage

The MAIN program calls REGION twice after assigning the value of the integer control parameter KRUN = 0 (Fig. 6.2a), which is passed to the subroutine through the labeled COMMON/CONTRL/.

After the first call by the MAIN program, with the value of the integer control parameter KRUN = 0, REGION initiates and completes the first part of the preparation stage according to the following three operational steps (Fig. 6.3a):

1. REGION reads the set of specified input data (Sect. 7.3) for all the geometric conditions associated with the main flow channel.
2. REGION reads the set of specified input data (Sect. 7.3) for the locations of the selected transect of the main flow channel.
3. REGION reads the set of specified input data (Sect. 7.3) for the detailed geometric representation of the bed contour of each cross-sectional transect as the specified vertical variations for all the positions along the "left bank" and the "right bank," according to the "spatially relative" vertical coordinate z of the particular cross section of the main flow channel.

The second part of the preparation stage of the modular subroutine REGION calculates the temporally constant geometric characteristics of the elements of the main flow channel based on the set of specified input data for geometric conditions according to the following two operational steps (Fig. 6.3a).

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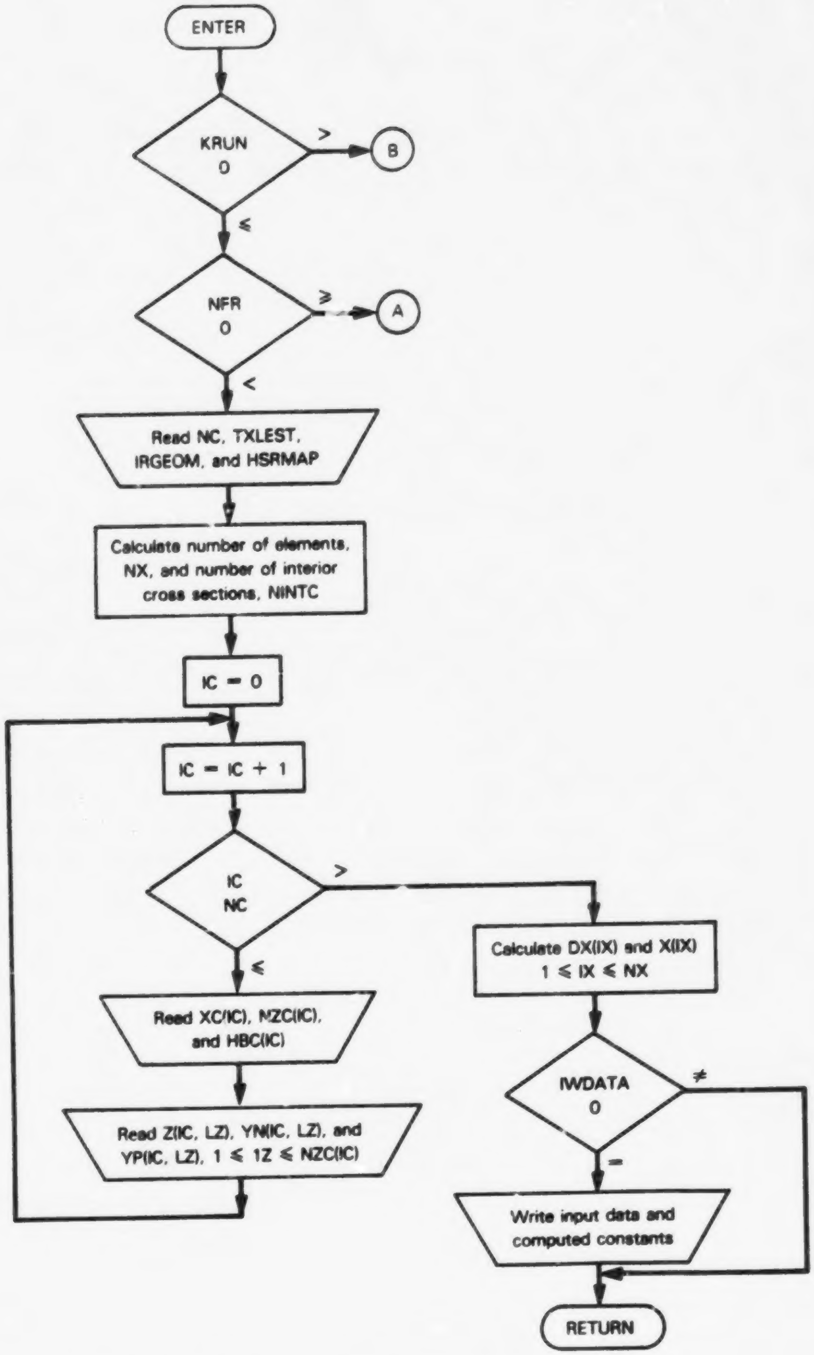
ENTER
KRUN
0
>
B
≤
NFR
0
≥
A
<
Read NC, TXLEST, IRGEOM, and HSRMAP
Calculate number of elements, NX, and number of interior cross sections, NINTC
IC = 0
IC = IC + 1
IC
NC
>
≤
Read XC(IC), NZC(IC), and HBC(IC)
Read Z(IC, LZ), YN(IC, LZ), and YP(IC, LZ), 1 ≤ 1Z ≤ NZC(IC)
Calculate DX(IX) and X(IX) 1 ≤ IX ≤ NX
IWDATA
0
≠
=
Write input data and computed constants
RETURN

Fig. 6.3a. Abbreviated flowchart of the structure and computational procedure of the modular subroutine REGION of the RADONE computer code.

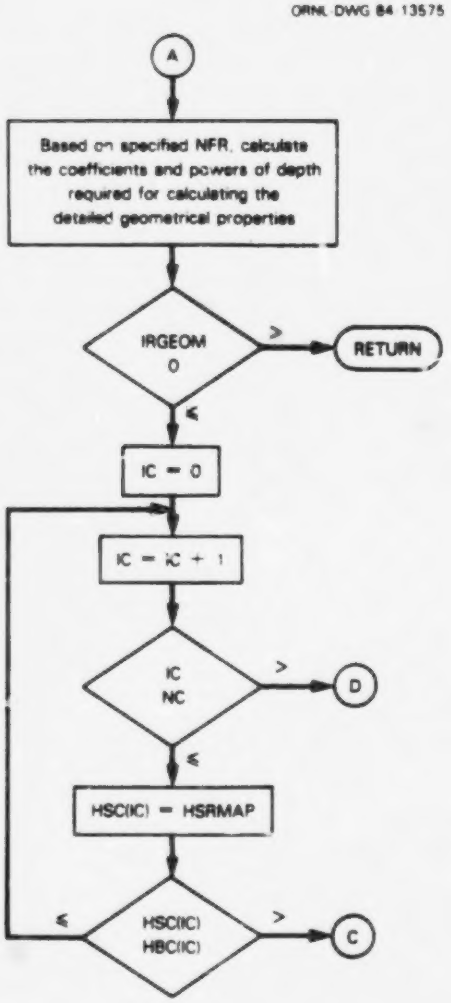
ORNL-DWG 84-13575
A
Based on specified NFR, calculate the coefficients and powers of depth required for calculating the detailed geometrical properties
IRGEOM
0
>
RETURN
≤
IC = 0
IC = IC + 1
IC
NC
>
D
≤
HSC(IC) = HSRMAP
≤
HSC(IC)
HBC(IC)
>
C

Fig. 6.3b. Abbreviated flowchart of the structure and computational procedure of the modular subroutine REGION of the RADONE computer code (continued).

4. REGION determines (a) NX = NC − 1 as the total number of elements corresponding to the total number of arbitrarily sized channel segments that collectively span the curvilinear longitudinal length TXLEST of the main flow channel and (b) NINTC = NC − 2 as the total number of internal cross sections, including the upstream- and downstream-end enclosure-surface cross sections of the main flow channel.
5. For all the elements IX = 1, ..., NX, REGION calculates (a) DX(IX) as the curvilinear length of the element IX (along the curvilinear longitudinal *x*-axis of the main flow channel), representing the curvilinear length of the channel segment (Figs. 2.1 and 2.2), and (b) X(IX) as the location of the center (relative to the arbitrarily specified origin of the curvilinear longitudinal *x*-axis of the main flow channel) of the discrete-element IX (Figs. 2.1 and 2.2).

The third part of the preparation stage of the modular subroutine REGION consists of the following operational step (Fig. 6.3a):

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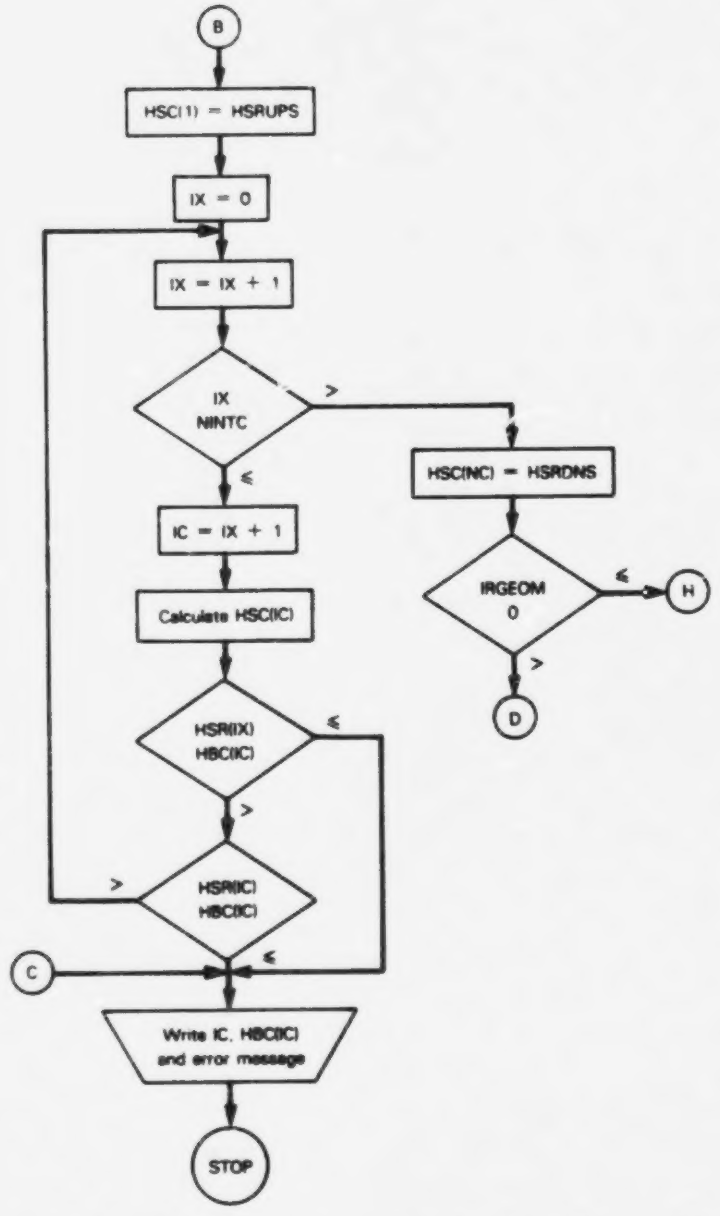
B
HSC(1) = HSRUPS
IX = 0
IX = IX + 1
IX
NINTC
>
≤
HSC(NC) = HSRDNS
IC = IX + 1
Calculate HSC(IC)
IRGEOM
0
≤
H
>
D
HSR(IX)
HBC(IC)
≤
>
HSR(IC)
HBC(IC)
>
≤
C
Write IC, HBC(IC)
and error message
STOP

Fig. 6.3c. Abbreviated flowchart of the structure and computational procedure of the modular subroutine REGION of the RADONE computer code (continued).

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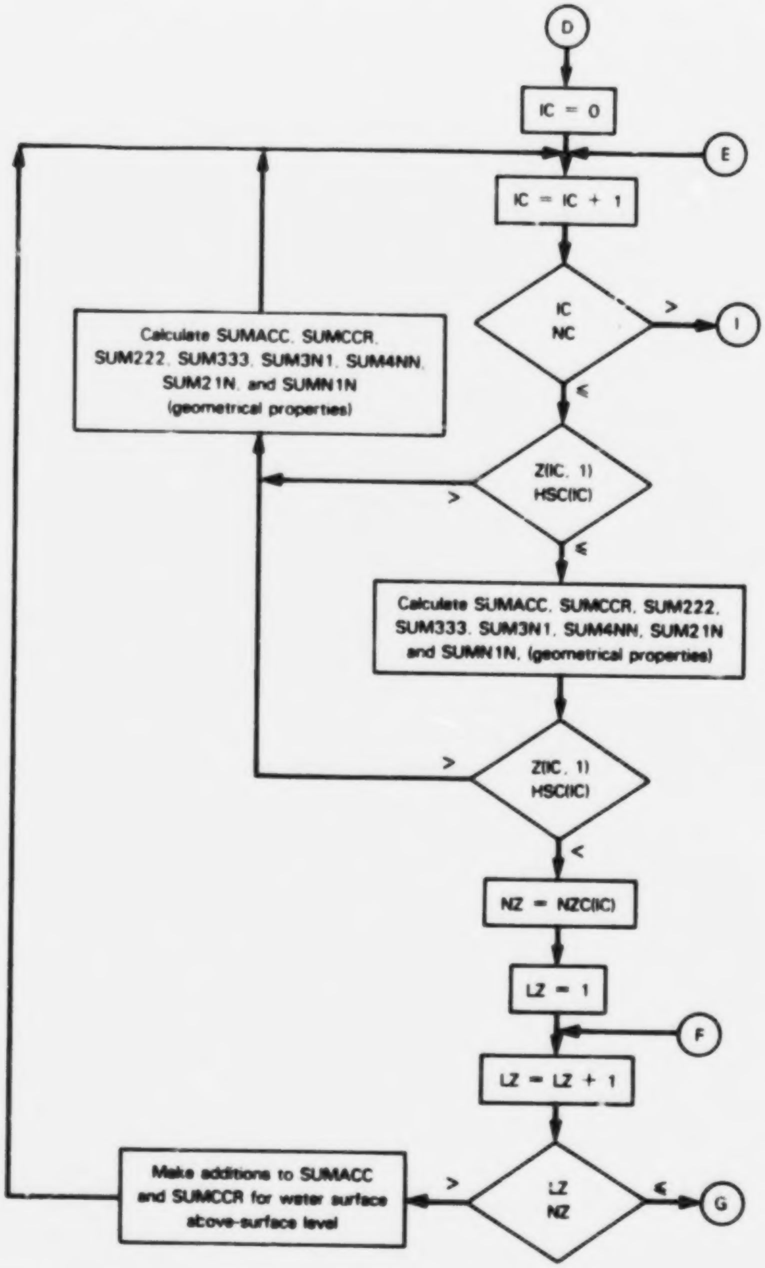
D
IC = 0
E
IC = IC + 1
IC
NC
>
I
≤
Calculate SUMACC, SUMCCR, SUM222, SUM333, SUM3N1, SUM4NN, SUM21N, and SUMN1N (geometrical properties)
Z(IC, 1)
HSC(IC)
>
≤
Calculate SUMACC, SUMCCR, SUM222, SUM333, SUM3N1, SUM4NN, SUM21N and SUMN1N, (geometrical properties)
>
Z(IC, 1)
HSC(IC)
<
NZ = NZC(IC)
LZ = 1
F
LZ = LZ + 1
Make additions to SUMACC and SUMCCR for water surface above-surface level
>
LZ
NZ
≤
G

Fig. 6.3d. Abbreviated flowchart of the structure and computational procedure of the modular subroutine REGION of the RADONE computer code (continued).

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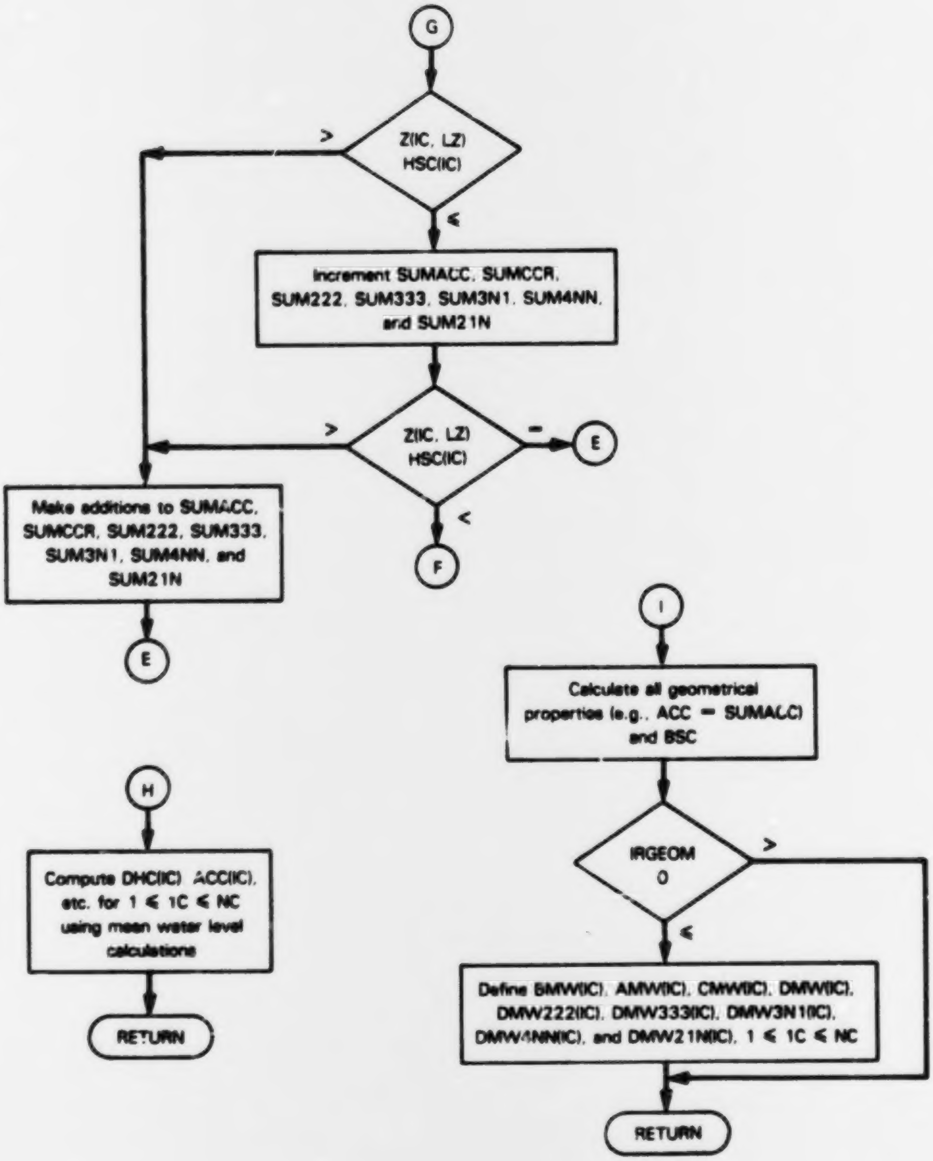
G
Z(IC, LZ)
HSC(IC)
>
≤
Increment SUMACC, SUMCCR, SUM222, SUM333, SUM3N1, SUM4NN, and SUM21N
Z(IC, LZ)
HSC(IC)
>
=
E
<
F
Make additions to SUMACC, SUMCCR, SUM222, SUM333, SUM3N1, SUM4NN, and SUM21N
E
I
Calculate all geometrical properties (e.g., ACC = SUMACC) and BSC
IRGEOM
0
>
≤
Define BMW(IC), AMW(IC), CMW(IC), DMW(IC), DMW222(IC), DMW333(IC), DMW3N1(IC), DMW4NN(IC), and DMW21N(IC), 1 ≤ 1C ≤ NC
RETURN
H
Compute DHC(IC) ACC(IC), etc. for 1 ≤ 1C ≤ NC using mean water level calculations
RETURN

Fig. 6.3e. Abbreviated flowchart of the structure and computational procedure of the modular subroutine REGION of the RADONE computer code (continued).

6. For the value of the integer control parameter IWDATA = 1, which is read in the MAIN program (Sect. 6.2) and passed through the labeled COMMON/PUTOUT/, REGION writes as printed output (Sect. 8.2) all specified input data and calculated values for the geometric properties of all elements IX = 1, ..., NX of the main flow channel; then, it returns to the MAIN program.

Because calculations of the detailed geometric properties of the cross-sectional areas of the elements require the value of the specified constant integer power NFR of the Blasius power-law-type vertical distribution of channel flow velocity (Sect. 3.3), the MAIN program, with the specified value of the integer control parameter KRUN = 0, calls the modular subroutine TURBUL (Sect. 6.8), which reads the value of NFR and returns to the MAIN program. The MAIN program then calls the modular subroutine REGION for the second time; the value of the specified constant integer power NFR is passed to the subroutine through the labeled COMMON/PARAMS/ (Appendix A). After the second call by the MAIN program, with the value of the integer control parameter KRUN = 0 and the value of the specified constant integer power NFR, REGION completes the fourth part of the preparation stage according to the following one or two operational steps (Fig. 6.3b):

7. Based on the value of the specified constant integer power NFR, REGION calculates all the constant coefficients and powers of depth that are used in subsequent calculations of the detailed geometric properties of the cross sections of the main flow channel (Sect. 3).
8. According to specified input data for the value of the integer control parameter IRGEOM for selecting the user-specified option for the trapezoidal integration scheme to be used in calculating the geometric properties over the "core area" part and "embayment area" part of the cross sections, REGION branches to one of two options. For the value of the integer control parameter IRGEOM > 0, REGION returns to the MAIN program. This value (IRGEOM > 0) indicates that the detailed geometric properties of each cross section (Sect. 3) would be calculated according to the general computational procedure by using the trapezoidal integration technique at every time level of the numerical solution of the governing system of discrete-element equations to integrate from the bottom of the main flow channel at maximum depth to the level of the water surface elevation HSR, without considering the core area part and embayment area part of the cross sections. However, for the value of the integer control parameter IRGEOM = 0, REGION initiates the calculations of the detailed geometric properties for the core area part of each cross section (Figs. 6.3b, 6.3d, and 6.3e). This value (IRGEOM = 0) indicates that the detailed geometric properties of each cross section (Sect. 3) would be calculated by considering the computationally efficient form of the trapezoidal integration technique, which eliminates repetitive calculations over the temporally uniform core area parts of the cross section. Based on the mean water level for water surface elevation at each cross section as HSRMAP, REGION completes the calculations and stores in the labeled COMMON/GEOMWL/ all the detailed geometric properties for the core area part of each cross section.

At the end of the preparation stage, after completing the computational procedure and storing in the labeled COMMON/GEOMWL/ all the detailed geometric properties of all the cross sections, REGION completes the necessary initialization procedures that would be required in the subsequent computation stage of the subroutine; then, it returns to the MAIN program.

6.3.2 Computation Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of RADONE, REGION is called (a) by the modular subroutine

SOLVER (Sect. 6.5) at every intermediate time level of the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5) and (b) by the modular subroutine OUTPUT (Sect. 6.13), which writes the computed results for the principal solution variables after each NTW time step (Sect. 6.2). At each call, the computation stage of REGION is completed according to the following two operational steps (Figs. 6.3c–6.3e):

1. Based on the already calculated values at every intermediate time level of the numerical integration (solution) of the governing system of discrete-element equations in the modular subroutine SOLVER or at the time level for writing the computed result of the principal solution variables, for the values of water surface elevation HSR(IX) in the elements, which is passed to the subroutine through the labeled COMMON/HSRSOL/ (see Appendix A), REGION calculates by linear interpolation (Sect. 2.3.1) and stores in the labeled COMMON/GEOEST/ (Fig. 6.3c) the values for water surface elevation HSC(IC) at the specified internal cross sections of the main flow channel. The values for water surface elevation in each pair of adjacent elements, as HSR(IX) and HSR(IX + 1), are compared with the specified input data stored in the labeled COMMON/GEOEST/ (see Appendix A) for the elevation of the bottom at maximum depth HBC(IC) of the cross section between the two adjacent elements (Fig. 6.3c). Hence, at any time level of the computations, if the water surface elevation HSR(IX) in an element (IX) becomes less than or equal to the value of the specified input data for (a) the elevation of the bottom at maximum depth HBC(IC) of the upstream-enclosure-surface cross section (IC) of the element (IX) and/or (b) the elevation of the bottom at maximum depth HBC(IC + 1) of the downstream-enclosure-surface cross section (IC + 1) of the element (IX), REGION writes an error message, which indicates the cross section (IC) and the elevation of the bottom at maximum depth HBC(IC); then, it terminates (STOP) the computational procedure of ESTONE (Fig. 6.3c).

2a. For the value of the integer control parameter IRGEOM = 0, according to the specified input data, REGION uses the computationally efficient, linearized forms (Fig. 6.3e) to calculate and store in the labeled COMMON/GEOEST/ the detailed geometric properties of every cross section.

2b. For the value of the integer control parameter IRGEOM = 1 (or > 0), REGION uses directly the trapezoidal integration technique for calculating the detailed geometric properties of every cross section by integrating from the bottom of the main flow channel at maximum depth to the level of the water surface elevation HSC(IC) at the cross section, and it calculates and stores in the labeled COMMON/GEOEST/ the detailed geometric properties of every cross section.

After completing the calculations according to the general trapezoidal integration technique of the detailed geometric properties of all the cross sections, REGION returns to the computational location of its call in the modular subroutine SOLVER (Sect. 6.5) or the modular subroutine OUTPUT (Sect. 6.13).

At the end of the computation stage, REGION completes the calculations and stores in the labeled COMMON/GEOEST/ all the detailed geometric properties of all the cross sections that would be required by the other modular subroutines of RADONE in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sects. 2, 3, and 5).

6.4 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE INITAL

The modular subroutine INITAL reads the set of specified input data to the RADONE computer code and/or determines the required initial conditions for the principal solution variables (Sect. 5.2). INITAL is only called from the MAIN program when the integer control parameter KRUN = 0; hence, its structure consists of only a preparation stage.

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In applications of RADONE to the simulation of hydrodynamic and radionuclide concentration conditions in a controlled river or a tidal estuary, it frequently becomes impossible to specify accurately all the required initial conditions for principal solution variables in all the elements that collectively span the total longitudinal length of the main flow channel. Hence, it frequently becomes necessary to assume a reasonable, but not necessarily accurate, set of specified input data for initial conditions of the principal solution variables (Sect. 5.2) and then to allow RADONE to proceed with the computer simulations until, at a time level sufficiently later than the initial time, the numerical integration (solution) of the governing discrete-element equations of the radionuclide transport model automatically leads to results that can accurately and realistically represent hydrodynamic and radionuclide concentration conditions in the main flow channel. Hence, a special user-specified option, based on the value of an integer control parameter ISTART, is included in the modular subroutine INITAL to enable the user to generate, with a minimum amount of effort, the required reasonable, but not necessarily accurate, set of specified input data for initial conditions of the principal solution variables (Sect. 5.2).

INITAL first reads (Fig. 6.4) a data record that contains the specified values for ISTART, HSRII, GFXIMX, GFXIPX, CRWIII, and CRBII (Sects. 5.2 and 7.4), which represent the reasonable, but not

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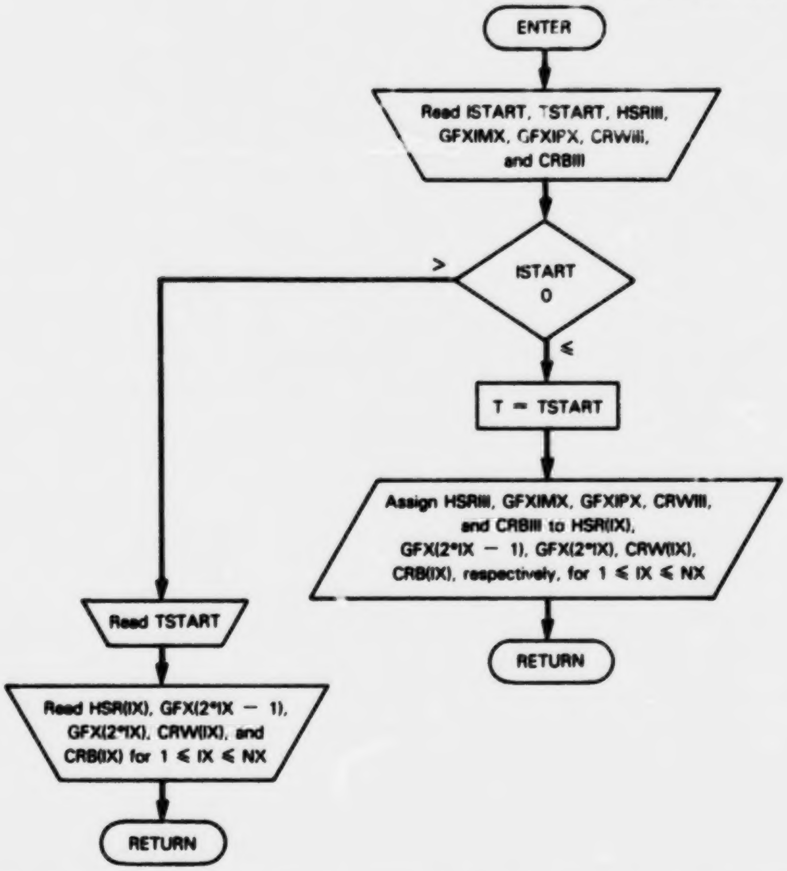
ENTER
Read ISTART, TSTART, HSRIII, GFXIMX, GFXIPX, CRWIII, and CRBIII
ISTART
0
>
≤
T = TSTART
Assign HSRIII, GFXIMX, GFXIPX, CRWIII, and CRBIII to HSR(IX), GFX(2*IX − 1), GFX(2*IX), CRW(IX), CRB(IX), respectively, for 1 ≤ IX ≤ NX
RETURN
Read TSTART
Read HSR(IX), GFX(2*IX − 1), GFX(2*IX), CRW(IX), and CRB(IX) for 1 ≤ IX ≤ NX
RETURN

Fig. 6.4. Abbreviated flowchart of the structure and computational procedure of the modular subroutine INITAL of the RADONE computer code.

necessarily accurate, set of specified input data for the initial conditions of the principal solution variables (Sect. 5.2), with ISTART as the integer control parameter for selecting the user-specified option for determining the initial conditions for the principal solution variables.

For the value of the integer control parameter ISTART < 0, according to the specified input data, INITAL sets time T = 0 (Fig. 6.4) and prepares the form of a reasonable, but not necessarily accurate, set of data for initial conditions of the principal flow variables by assuming that the values of the principal flow variables in all elements of the main flow channel are equal to the reasonable, approximate values of the principal flow variables as specified in the set of input data. Hence, INITAL completes the preparation of the required initial conditions of the principal flow variables (Sect. 5.2 and Fig. 6.4) by assuming that

1. the values of water surface elevation HSR(IX), in all the elements IX = 1, ..., NX are equal to the reasonable, approximate value of water surface elevation for all the elements of the main flow channel HSRIII (this information is stored in the labeled COMMON/HSRSOL/),
2. the values of channel flow rate GFX(IMX) in all the upstream half-elements IMX = 1, 3, ..., 2*NX − 1 are equal to the reasonable, approximate value of channel flow rate for all the upstream half-elements of the main flow channel GFXIMX (this information is stored in the labeled COMMON/GFXSOL/),
3. the values of channel flow rate GFX(IPX) in all the downstream half-elements IPX = 2, 4, ..., 2*NX are equal to the reasonable, approximate value of channel flow rate for all the downstream half-elements of the main flow channel GFXIPS (this information is stored in the labeled COMMON/GFXSOL/),
4. the values of the water concentration of the radionuclide in the water layer CRW(IX) in all the elements IX = 1, ..., NX are equal to the reasonable, approximate value of water concentration of the radionuclide in the water layer for all the elements of the main flow channel CRWII (this information is stored in the labeled COMMON/CRWSOL/), and
5. the values of the bottom concentration of the radionuclide in the bottom layer CRB(IX) in all the elements IX = 1, ..., NX are equal to the reasonable approximate value of bottom concentration of the radionuclide in the bottom layer for all the elements of the main flow channel. (This information is stored in labeled COMMON/CRBSOL/.) After completing the preparation of initial conditions of the principal flow variables (Sect. 5.2), INITAL returns to the MAIN program.

For the value of the integer control parameter ISTART = 1 (or > 0), according to the specified input data, INITAL reads the detailed set of specified input data (Fig. 6.4 and Sect. 7.4) for the actual initial time T and the accurate initial conditions for all the principal solution variables (Sect. 5.2), individually, in each element and half-element of the main flow channel. These variables are

1. HSR(IX) as water surface elevation in the element IX, which is stored in the labeled COMMON/HSRSOL/,
2. GFX(IMX) as channel flow rate in the upstream half-element IMX = 2*IX − 1, which is stored in the labeled COMMON/GFXSOL/,
3. GFX(IPX) as channel flow rate in the downstream half-element IPX = 2*IX, which is stored in the labeled COMMON/GFXSOL/,
4. CRW(IX) as water concentration of the radionuclide in the water layer in the element IX, which is stored in the labeled COMMON/CRWSOL/, and
5. CRB(IX) as bottom concentration of the radionuclide in the bottom layer in the element IX, which is stored in the labeled COMMON/CRBSOL/.

After reading the detailed set of specified input data for the initial conditions of the principal solution variables (Sect. 5.2), INITAL again returns to the MAIN program.

The detailed specified input data (Sect. 7.4) for the actual initial time T and the accurate initial conditions for the principal solution variables (Sect. 5.2) are also used as the restart data set for the initial conditions in successive applications of ESTONE. The restart data set for the initial conditions of the principal solution variables (Sect. 5.2) is automatically generated with the appropriate format by the modular subroutine OUTPUT (Sect. 6.13), according to the final call in the termination stage of the MAIN program, when the integer control parameter KRUN = 2 (Sect. 6.2).

It is important that the initial time T cannot be specified arbitrarily in the application of RADONE to the simulations of detailed and realistic hydrodynamic and radionuclide concentration conditions in a controlled river or a tidal estuary. Because the input data required to specify (a) upstream-end and downstream-end conditions, (b) transport conditions on the water surface, and (c) operational conditions and radionuclide release conditions generally at the plants would include different temporal variations, the specification of the initial time T must be consistent with the specifications of all the different temporal variations of all the specified input data. Hence, it is convenient to consider the general time T relative to 00:00 h as midnight on a certain specified date and then to determine the temporal variations of all the specified input data (Sect. 7) and the initial time T based on this specified zero hour in all the subsequent, successive applications of RADONE.

6.5 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE SOLVER

The modular subroutine SOLVER includes the fundamental computational solution algorithm of ESTONE, based on the fourth-order Runge-Kutta-Gill method [e.g., Conte and deBoor (1972)], which is used in the numerical integration (solution) of the 5*N*-dimensional vector, first-order initial-value problem [Eqs. (5.41) and (5.42)] associated with the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2).

The structure and the computational procedure of SOLVER (Figs. 6.5a–6.5c) consist of two operational stages, the preparation stage and computation stage, which are initiated and completed, depending on the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/. The argument list of SOLVER consists of (1) TS as the specified time for starting the numerical integration, based on the fourth-order Runge-Kutta-Gill method [e.g., Conte and deBoor (1972)], and (2) DT as the specified duration of the numerical integration, which represents the specified time step of the numerical integration (solution) of the governing system of discrete-element equations (Sect. 5.2) of the radionuclide transport model. Based on this argument list, SOLVER internally determines the time level at each of the four computational steps associated with the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)] and passes the required value of the time level to all the modular subroutines of RADONE through the labeled COMMON/CONTRL/.

6.5.1 Preparation Stage

The modular subroutine SOLVER is first called from the MAIN program, with the value of the integer control parameter KRUN = 0 (Fig. 6.2), which is passed to the subroutine through the labeled COMMON/CONTRL/. SOLVER does not read any specified input data, and it initiates and completes the preparation stage internally, according to the following two operational steps (Fig. 6.5a):

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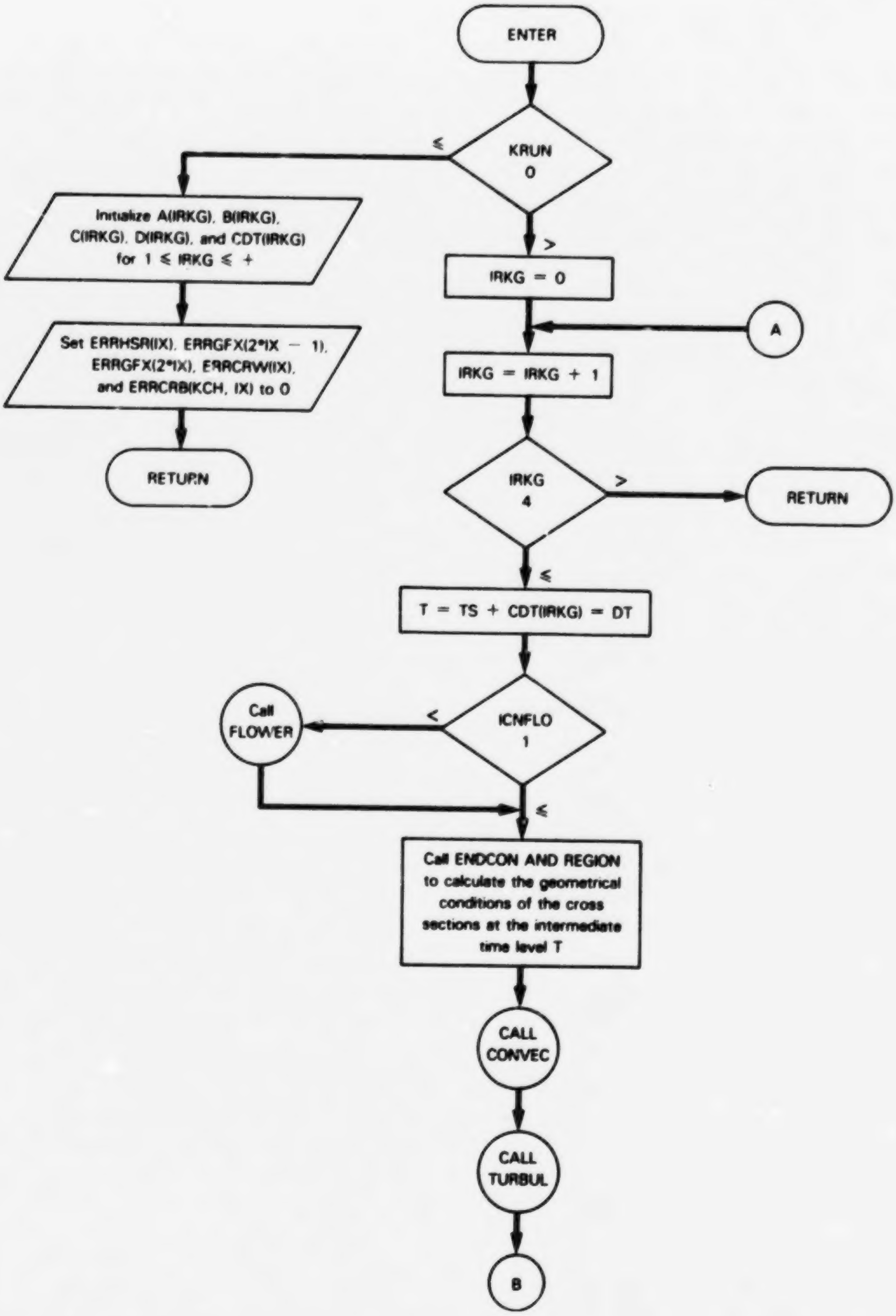
ENTER
KRUN
0
≤
>
Initialize A(IRKG), B(IRKG),
C(IRKG), D(IRKG), and CDT(IRKG)
for 1 ≤ IRKG ≤ +
Set ERRHSR(IX), ERRGFX(2*IX − 1),
ERRGFX(2*IX), ERRCRW(IX),
and ERRCRB(KCH, IX) to 0
RETURN
IRKG = 0
A
IRKG = IRKG + 1
IRKG
4
>
RETURN
≤
T = TS + CDT(IRKG) = DT
Call
FLOWER
<
ICNFLO
1
≤
Call ENDCON AND REGION
to calculate the geometrical
conditions of the cross
sections at the intermediate
time level T
CALL
CONVEC
CALL
TURBUL
B

Fig. 6.5a. Abbreviated flowchart of the structure and computational procedure of the modular subroutine SOLVER of the RADONE computer code.

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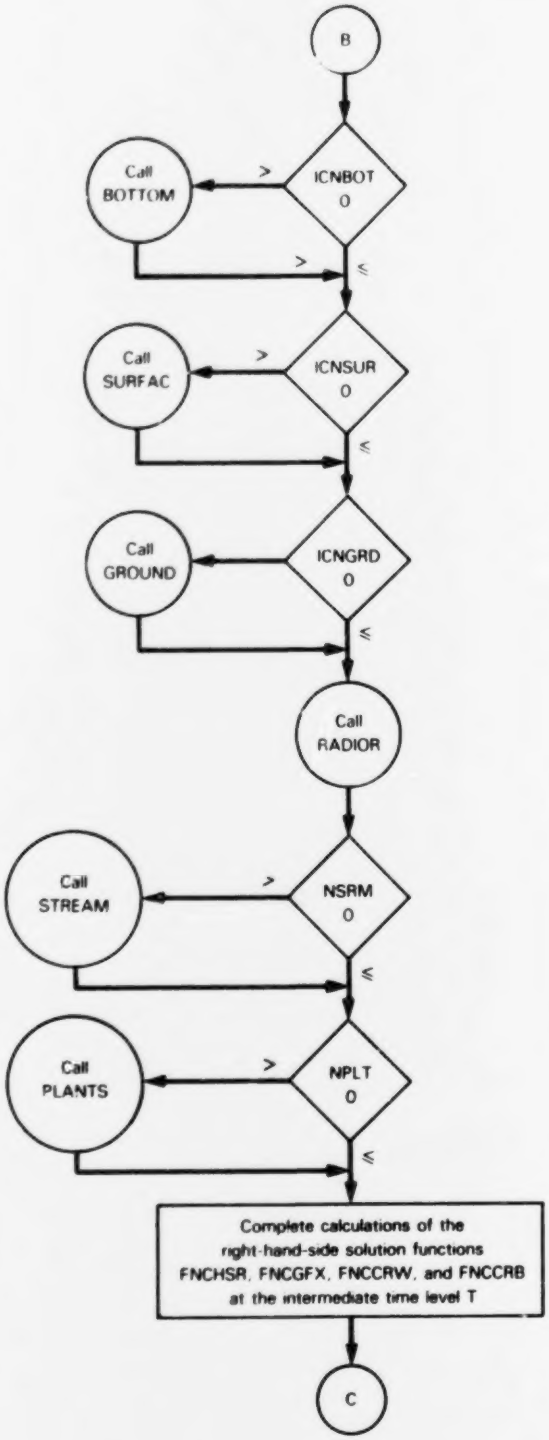
B
ICNBOT
0
>
≤
Call
BOTTOM
ICNSUR
0
Call
SURFAC
ICNGRD
0
Call
GROUND
Call
RADIOR
NSRM
0
Call
STREAM
NPLT
0
Call
PLANTS
Complete calculations of the
right-hand-side solution functions
FNCHSR, FNCGFX, FNCCRW, and FNCCRB
at the intermediate time level T
C

Fig. 6.5b. Abbreviated flowchart of the structure and computational procedure of the modular subroutine SOLVER of the RADONE computer code (continued).

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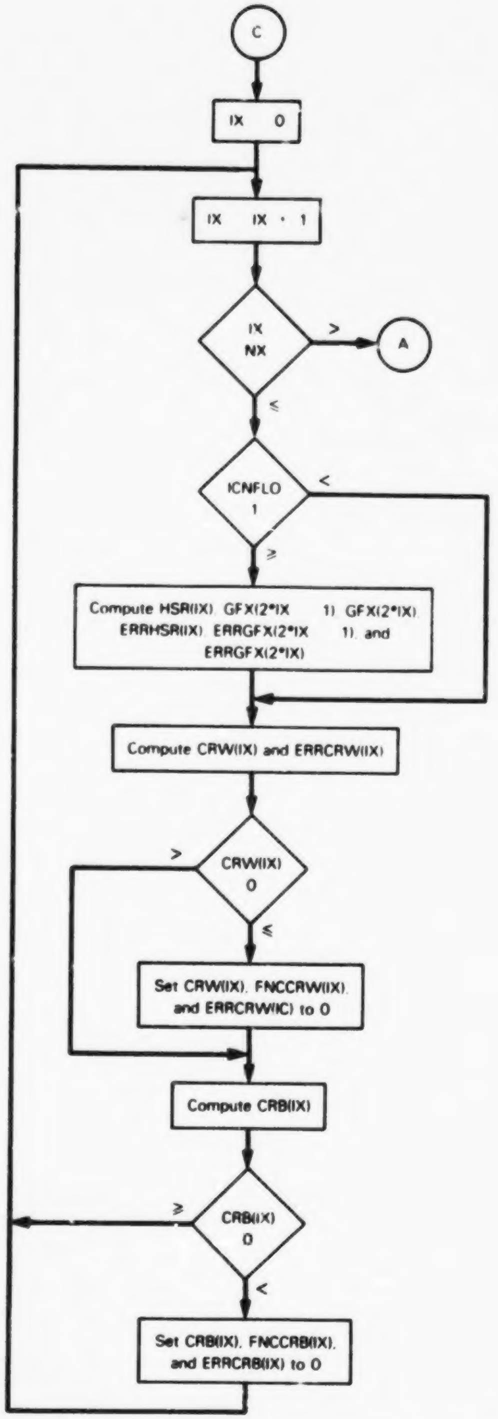
C
IX 0
IX IX · 1
IX
NX
>
A
≤
ICNFLO
1
<
≥
Compute HSR(IX), GFX(2*IX 1), GFX(2*IX), ERRHSR(IX), ERRGFX(2*IX 1), and ERRGFX(2*IX)
Compute CRW(IX) and ERRCRW(IX)
>
CRW(IX)
0
≤
Set CRW(IX), FNCCRW(IX), and ERRCRW(IC) to 0
Compute CRB(IX)
≥
CRB(IX)
0
<
Set CRB(IX), FNCCRB(IX), and ERRCRB(IX) to 0

Fig. 6.5c. Abbreviated flowchart of the structure and computational procedure of the modular subroutine SOLVER of the RADONE computer code (continued).

1. SOLVER assigns appropriate values to all the computational coefficients associated with the mathematical formulation of the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)].
2. SOLVER initializes to zero the values of all the truncation error terms in each element (Fig. 6.5a). There errors are
   a. HSRERR(IX) = 0 as the truncation error for water surface elevation HSR(IX) in the element IX, which is stored in the labeled COMMON/HSRSOL/,
   b. ERRGFX(IMX) = 0 as the truncation error for channel flow rate GFX(IMX) in the upstream half-element IMX = 2*IX − 1, which is stored in the labeled COMMON/GFXSOL/,
   c. ERRGFX(IPX) = 0 as the truncation error for channel flow rate GFX(IPX) in the downstream half-element IPX = 2*IX, which is stored in the labeled COMMON/GFXSOL/,
   d. ERRCRW(IX) = 0 as the truncation error for the water concentration of the radionuclide in the water layer CRW(IX) in the element IX, which is stored in the labeled COMMON/CRWSOL/, and
   e. ERRCRB(IX) = 0 as the truncation error for the bottom concentration of the radionuclide in the bottom layer CRB(IX) in the element IX, which is stored in the labeled COMMON/CRBSOL/.

At the end of the preparation stage, SOLVER completes all the necessary initialization procedures that would be required in the subsequent computational stage of the subroutine; then, it returns to the MAIN program.

6.5.2 Computation Stage

SOLVER is called NT times from the MAIN program (Sect. 6.2), with the integer control parameter KRUN = 1, during the main computational procedure of RADONE, associated with the numerical integration (solution) of the governing discrete-element equations of the radionuclide transport model (Sect. 5.2), for the specified total duration of the computer simulations.

At each call from the MAIN program, during the main computational procedure of RADONE, SOLVER repeats four times the identical computational procedure with four different sets of computational coefficients that were specified in the preparation stage of the subroutine according to the four stages of the computational algorithm of the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)].

The first part of the computational procedure that is repeated four times consists of the following three operational steps (Fig. 6.5a):

1. SOLVER first calculates and stores, in the labeled COMMON/CONTRL/, the intermediate time level T (Fig. 6.5a) associated with one of the four stages of the computational algorithm of the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)].
2. SOLVER calls the modular subroutine ENDCON (Sect. 6.6), which determines at the intermediate time level T (which is passed to ENDCON through the labeled COMMON/CONTRL/) all the required upstream-end and downstream-end conditions of the principal flow variables (Sect. 4.3), which are passed to the appropriate modular subroutines through the labeled COMMON/ENDFLO/ (Appendix A).
3. SOLVER calls the modular subroutine REGION (Sect. 6.3), which calculates all the required geometric properties of all the cross sections of the main flow channel at the intermediate time level T (Fig. 6.5a).

The second part of the computational procedure that is repeated four times according to the four stages of the computational algorithm of the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)], during each call of the modular subroutine SOLVER, initiates and completes the computational sequence of the eight major modular subroutines associated with the eight different radionuclide transport phenomena and the radiological decay phenomenon that occurs in the elements and half-elements of the main flow channel (Sect. 5.2). The computational procedure of SOLVER uses a sequential computational method based on a successive updating scheme (Sect. 5.2) for the right-hand-side solution function vectors (slopes in the time and principal-flow-variable space) by calling successively the eight modular subroutines CONVEC, TURBUL, BOTTOM, SURFAC, GROUND, RADIOR, STREAM, and PLANTS, which successively calculate the contribution of the eight different phenomena that control the flow and the radionuclide transport conditions in the 2*NX number of half-elements and NX number of elements, respectively, according to the one-dimensional formulation of the discrete-element radionuclide transport model of RADONE.

At the end of the second part of the computational procedure that is repeated four times, according to the four stages of the computational algorithm of the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)], the sequential computational method completes the calculation and storage of all right-hand-side solution functions (Figs. 6.5a and 6.5b), based on the successive updating scheme. The right-hand-side solution functions are

1. FNCHSR(IX) as the right-hand-side solution functions for water surface elevations HSR(IX) in all elements IX = 1, ..., NX [Eq. (5.6)], which are stored in the labeled COMMON/HSRSOL/,
2. FNCGFX(IMX) as the right-hand-side solution functions for channel flow rates GFX(IMX) in all the upstream half-elements IMX = 1, 3, ..., 2*NX − 1 [Eq. (5.13)], which are stored in the labeled COMMON/GFXSOL/,
3. FNCGFX(IPX) as the right-hand-side solution functions for channel flow rates GFX(IPX) in all the downstream half-elements IPX = 2, 4, ..., 2*NX [Eq. (5.20)], which are stored in the labeled COMMON/GFXSOL/,
4. FNCCRW(IX) as the right-hand-side solution functions for the water concentration of the radionuclide in the water layer CRW(IX) in all the elements IX = 1, ..., NX [Eq. (5.27)], which are stored in the labeled COMMON/CRWSOL/, and
5. FNCCRB(IX) as the right-hand-side solution functions for the bottom concentration of the radionuclide in the bottom layer CRB(IX) in all the elements IX = 1, ..., NX [Eq. (5.34)], which are stored in labeled COMMON/CRBSOL/.

According to the user-specified option for excluding the solution of hydrodynamic conditions (Sects. 5.3 and 6.2), an auxiliary operational step is also included (Fig. 6.5a). For the integer control parameter ICNFLO = 0, which is read in the MAIN program and passed to the modular subroutine SOLVER through the labeled COMMON/CONTRL/, SOLVER calls the modular subroutine FLOWER, which calculates and stores the values of the principal flow variables associated with hydrodynamic conditions. These variables are

1. HSR(IX) as water surface elevations in all the elements IX = 1, ..., NX, which are stored in the labeled COMMON/HSRSOL/,
2. GFX(IMX) as channel flow rates in all the upstream half-elements IMX = 1, 3, ..., 2*NX − 1, which are stored in the labeled COMMON/GFXSOL/, and
3. GFX(IPX) as channel flow rates in all the downstream half-elements IPX = 2, 4, ..., 2*NX, which are stored in the labeled COMMON/GFXSOL/.

The third part of the computational procedure that is repeated four times during each call of the modular subroutine SOLVER completes the necessary calculations at each one of the four intermediate time levels to obtain (1) the solution of the principal solution variables and (2) the values of the truncation errors associated with the principal flow variables, based on the computational algorithm of the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)].

Computations of the principal solution variables associated with hydrodynamic conditions are included or excluded depending on the value of the integer control parameter ICNFLO, which is read in the MAIN program and passed to SOLVER through the labeled COMMON/CONTRL/. For the value of the integer control parameter ICNFLO = 0, which indicates the user-specified option for excluding the solution of hydrodynamic conditions, the third part of the computational procedure that is repeated four times omits the operational steps which are associated with the calculations of the hydrodynamic conditions (Fig. 6.5c). However, for the value of the integer control parameter ICNFLO = 1 (or > 0), which indicates the user-specified option for including the solution of hydrodynamic conditions, the third part of the computational procedure, which is repeated four times, includes the necessary operational steps associated with the calculations of the hydrodynamic conditions (Fig. 6.5c).

At the end of the computation stage, after the computational procedure associated with the fourth-order Runge-Kutta-Gill numerical integration method [e.g., Conte and deBoor (1972)] is repeated four times, SOLVER completes (1) the solution of the principal solution variables and (2) the calculation of the values of the truncation errors for the principal solution variables at the time level T = TS + DT; then, it returns to the MAIN program. The calculated principal flow variables are

1. water surface elevation HSR(IX) in all the elements IX = 1, ..., NX, which is stored in the labeled COMMON/HSRSOL/,
2. channel flow rate GFX(IMX) in all the upstream half-elements IMX = 1, 3, ..., 2*NX − 1, which is stored in the labeled COMMON/GFXSOL/,
3. channel flow rate GFX(IPX) in all the downstream half-elements IPX = 2, 4, ..., 2*NX, which is stored in the labeled COMMON/GFXSOL/,
4. water concentration of the radionuclide in the water layer CRW(IX) in all the elements IX = 1, ..., NX, which is stored in the labeled COMMON/CRWSOL/, and
5. bottom concentration of the radionuclide in the bottom layer CRB(IX), in all the elements IX = 1, ..., NX, which is stored in the labeled COMMON/CRBSOL/.

The calculated truncation errors for the principal solution variables are

1. the truncation error for water surface elevation ERRHSR(IX) in all the elements IX = 1, ..., NX, which is stored in the labeled COMMON/HSRSOL/,
2. the truncation error for channel flow rate ERRGFX(IMX) in all the upstream half-elements IMX = 1, 3, ..., 2*NX − 1, which is stored in the labeled COMMON/GFXSOL/,
3. the truncation error for channel flow rate ERRGFX(IPX) in all the downstream half-elements IPX = 2, 4, ..., 2*NX, which is stored in the labeled COMMON/GFXSOL/,
4. the truncation error for the water concentration of the radionuclide in the water layer ERRCRW(IX) in all the elements IX = 1, ..., NX, which is stored in the labeled COMMON/CRWSOL/, and
5. the truncation error for the bottom concentration of the radionuclide in the bottom layer ERRCRB(IX) in all the elements IX = 1, ..., NX, which is stored in the labeled COMMON/CRBSOL/.

A more extensive and detailed presentation of the structure and computational procedure of the modular subroutine is included in the users manual for the ESTONE computer code of the fast-transient, one-dimensional, discrete-element model for simulating the hydrodynamic, thermal, and salinity conditions in controlled rivers and tidal estuaries [Eraslan (1983)].

6.6 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE ENDCON

The modular subroutine ENDCON represents the computational procedure associated with the general formulation of specified end conditions (Sect. 4.3) that can consider three separate cases (as user-specified options): (1) simple closed-dam conditions, (2) controlled-flow dam conditions, and (3) tidal flow conditions. These three options collectively include all possible types of flow conditions and radionuclide concentration conditions that can exist at the upstream end and/or downstream end of the main flow channel of a controlled river and/or a tidal estuary. By using available information about the upstream-end and downstream-end conditions of the main flow channel, ENDCON can specify temporal variations of the principal solution variables to any desired level of accuracy.

The definitions of the parameters, associated with the formulations of the end conditions, which are included in the sets of specified input data to the RADONE code, will not be repeated in this section for the presentation of the structure and computational procedure of the modular subroutine ENDCON because the detailed definitions of all the required parameters are included in Sect. 7.6, which presents the discussions of the specified input data for the modular subroutine ENDCON. Furthermore, since an extensive and detailed presentation of the general structure and computational procedure of ENDCON for all fast-transient, one-dimensional transport models of the UTA project [Eraslan et al. (1976), Eraslan and Witten (1984)] is presented in the users manual of the ESTONE computer code [Eraslan (1983)] of the thermal program of UTA, this section will only present the structure and computational procedure of the modular subroutine ENDCON in a summary form, which would include all the necessary information that would be required by the user in implementing the RADONE computer code.

The structure and computational procedure of ENDCON (Figs. 6.6a–6.6f) consist of two operational stages, preparation stage and computation stage, which are initiated and completed, depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.6.1 Preparation Stage

The modular subroutine ENDCON is first called from the MAIN program with the value of the integer control parameter KRUN = 0 (Fig. 6.2), which is passed to the subroutine through the labeled COMMON/CONTRL/.

ENDCON initiates the first part of the preparation stage for reading in the specified input data (Sect. 4.3) according to the following three operational steps (Fig. 6.6a):

1. ENDCON reads the set of input data (Sect. 7.6) associated with the user-specified options for specifying upstream-end and downstream-end conditions (Sect. 4.3). The specified input data for the control parameters, associated with the user-specified options (Sect. 4.3) include IUPCON, IDNCON, and HSRMWL (Sect. 7.6) that are required for specifying one of the three cases of end conditions for the upstream end and/or the downstream end of the main flow channel.

ORNL DWG 84 14083

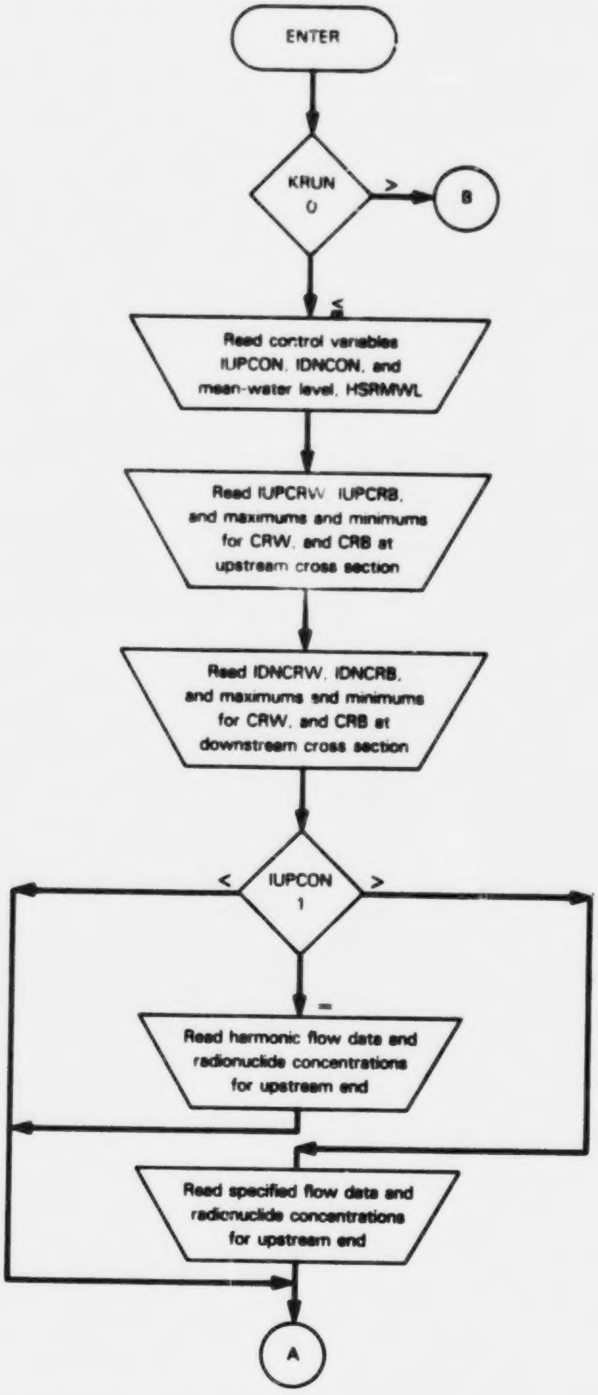
ENTER
KRUN
0
>
B
≤
Read control variables IUPCON, IDNCON, and mean-water level, HSRMWL
Read IUPCRW, IUPCRB, and maximums and minimums for CRW, and CRB at upstream cross section
Read IDNCRW, IDNCRB, and maximums and minimums for CRW, and CRB at downstream cross section
<
IUPCON
1
>
=
Read harmonic flow data and radionuclide concentrations for upstream end
Read specified flow data and radionuclide concentrations for upstream end
A

Fig. 6.6a. Abbreviated flowchart of the structure and computational procedure of the modular subroutine ENDCON of the RADONE computer code.

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ORNL DWG 84-14085

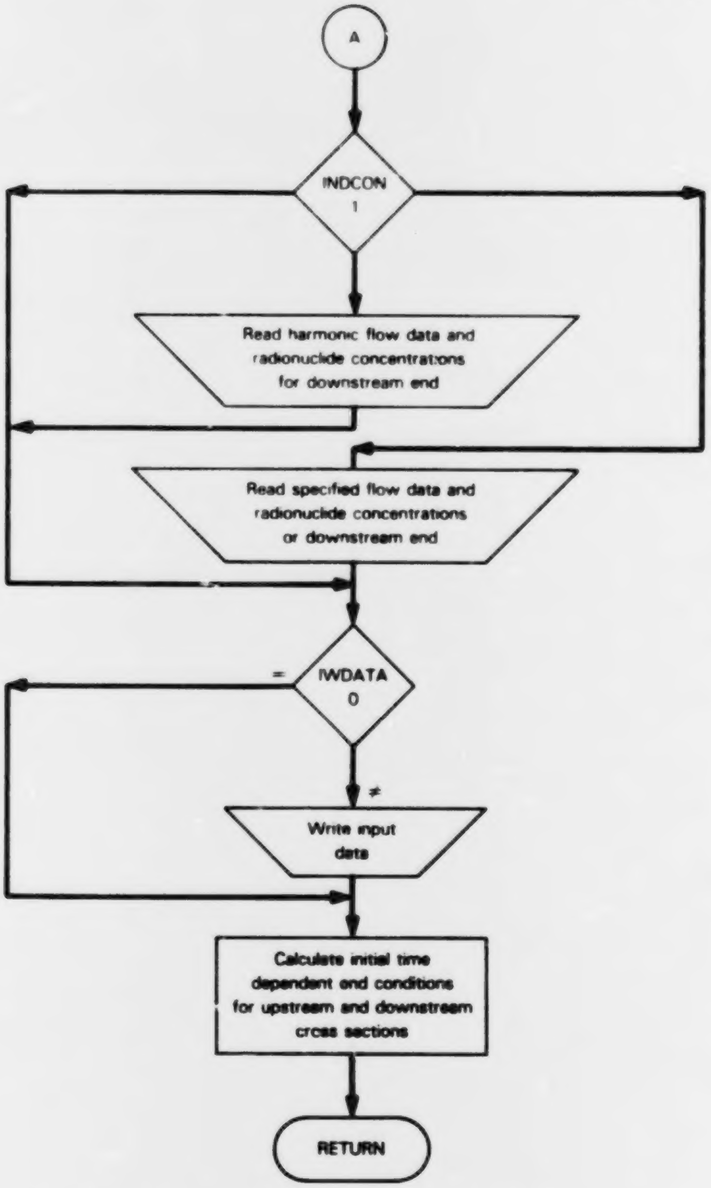
A
INDCON
1
Read harmonic flow data and radionuclide concentrations for downstream end
Read specified flow data and radionuclide concentrations or downstream end
=
IWDATA
0
≠
Write input data
Calculate initial time dependent end conditions for upstream and downstream cross sections
RETURN

Fig. 6.6b. Abbreviated flowchart of the structure and computational procedure of the modular subroutine ENDCON of the RADONE computer code (continued).

ORNL DWG 84-14087

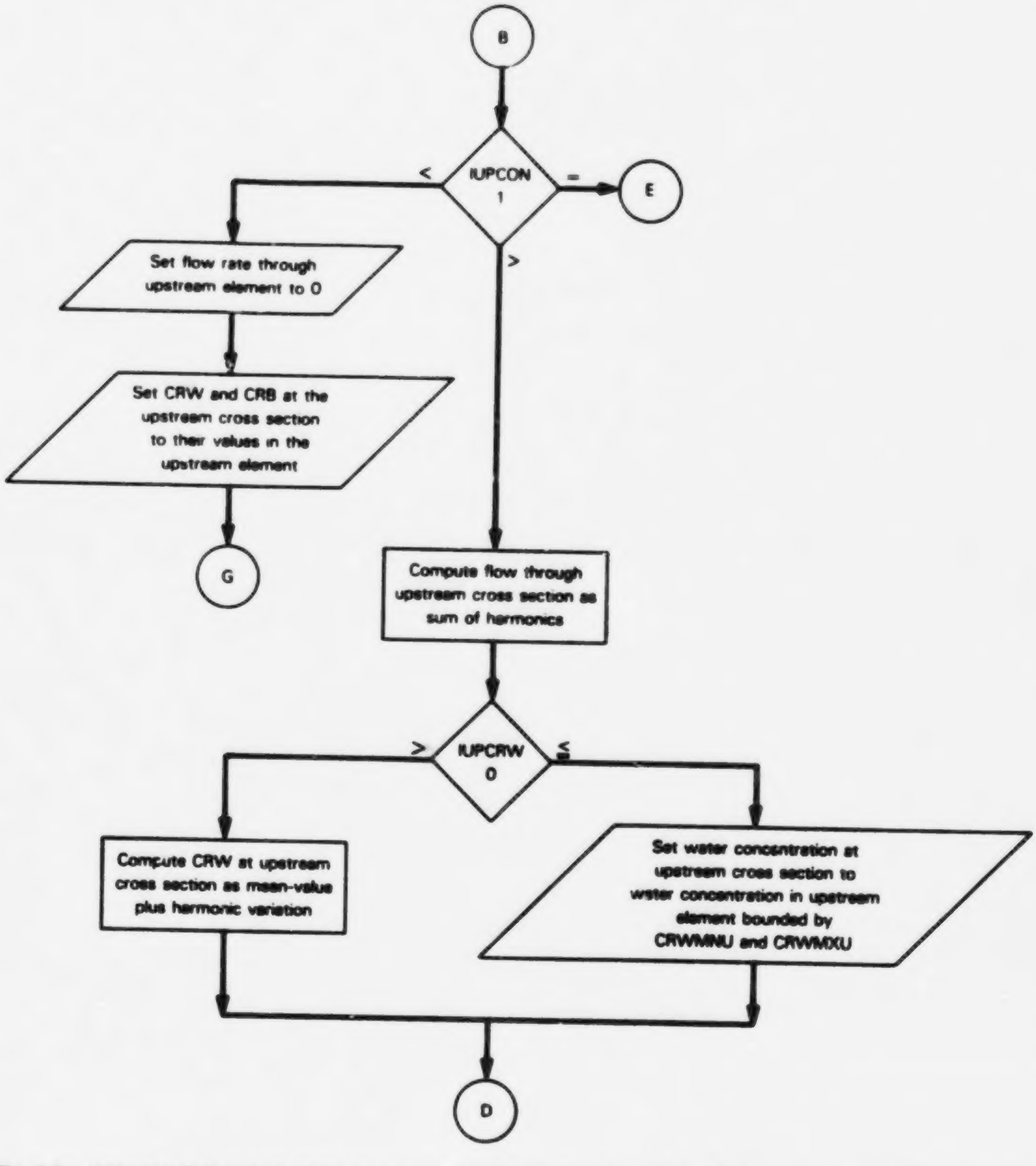
B
IUPCON
1
<
=
>
E
Set flow rate through upstream element to 0
Set CRW and CRB at the upstream cross section to their values in the upstream element
G
Compute flow through upstream cross section as sum of harmonics
IUPCRW
0
>
≤
Compute CRW at upstream cross section as mean-value plus harmonic variation
Set water concentration at upstream cross section to water concentration in upstream element bounded by CRWMINU and CRWMXU
D

Fig. 6.6c. Abbreviated flowchart of the structure and computational procedure of the modular subroutine ENDCON of the RADONE computer code (continued).

ORNL DWG 84 14084

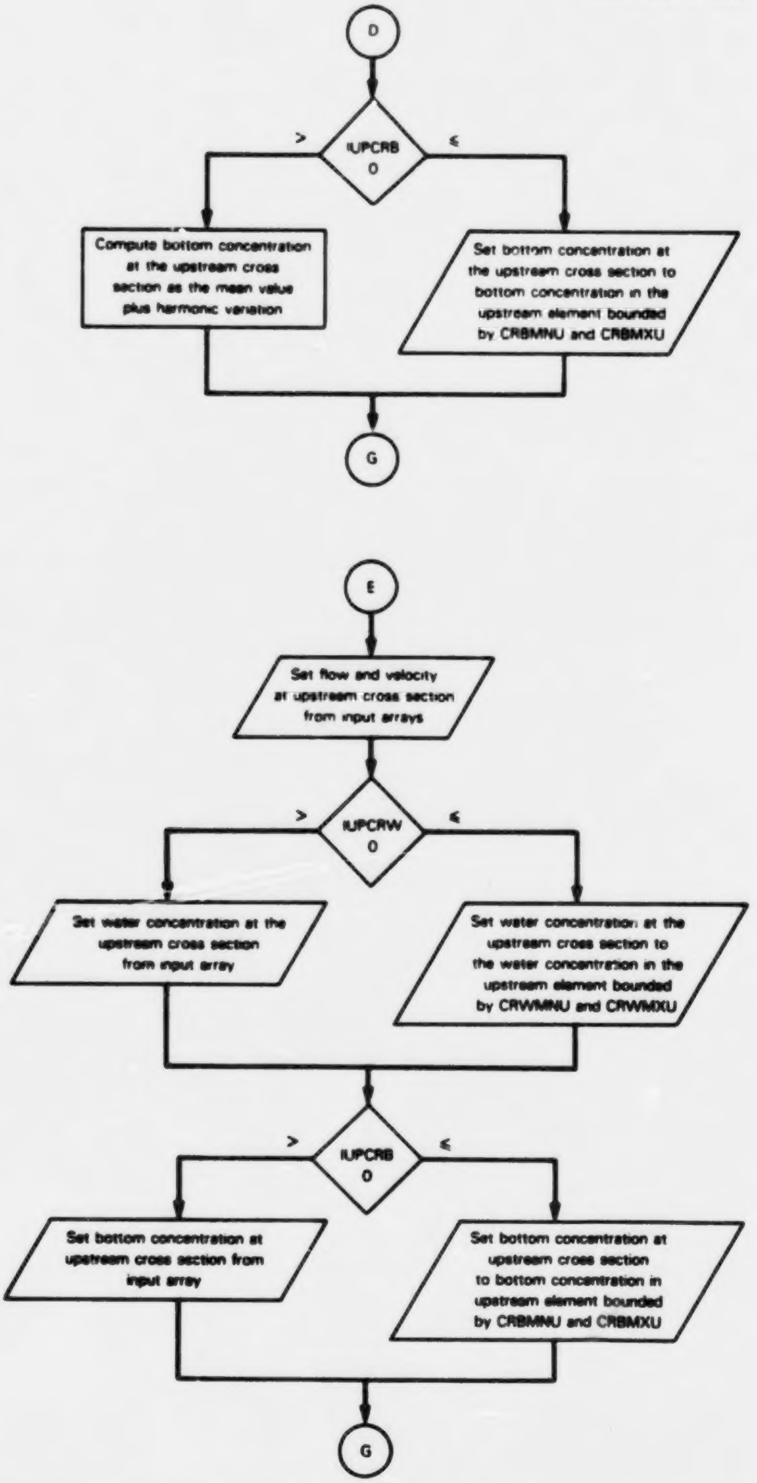
D
IUPCRB
0
>
≤
Compute bottom concentration at the upstream cross section as the mean value plus harmonic variation
Set bottom concentration at the upstream cross section to bottom concentration in the upstream element bounded by CRBMNU and CRBMXU
G
E
Set flow and velocity at upstream cross section from input arrays
IUPCRW
0
>
≤
Set water concentration at the upstream cross section from input array
Set water concentration at the upstream cross section to the water concentration in the upstream element bounded by CRWMNU and CRWMXU
IUPCRB
0
>
≤
Set bottom concentration at upstream cross section from input array
Set bottom concentration at upstream cross section to bottom concentration in upstream element bounded by CRBMNU and CRBMXU
G

Fig. 6.8d. Abbreviated flowchart of the structure and computational procedure of the modular subroutine ENDCON of the RADONE computer code (continued).

ORNL-DWG 84-14093

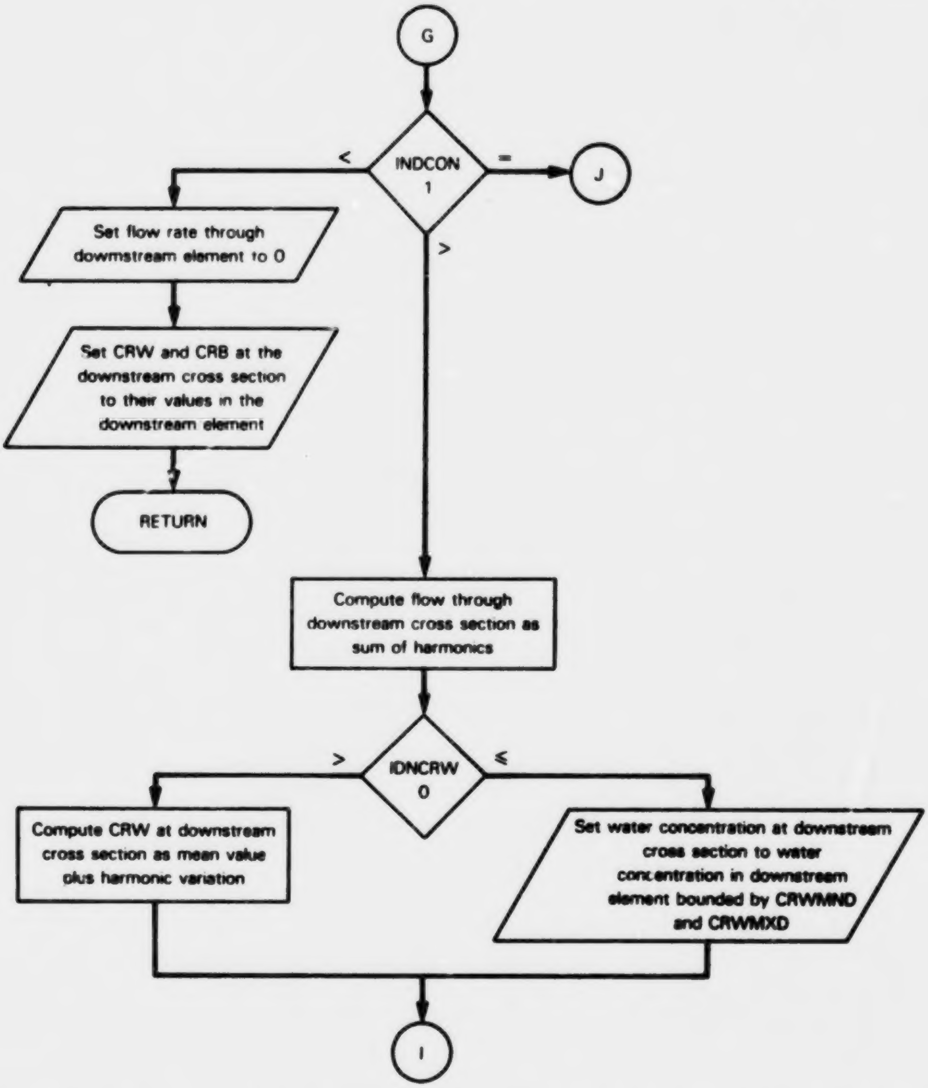
G
INDCON
1
<
=
>
J
Set flow rate through downmstream element to 0
Set CRW and CRB at the downstream cross section to their values in the downstream element
RETURN
Compute flow through downstream cross section as sum of harmonics
IDNCRW
0
>
≤
Compute CRW at downstream cross section as mean value plus harmonic variation
Set water concentration at downstream cross section to water concentration in downstream element bounded by CRWMND and CRWMXD
I

Fig. 6.6e. Abbreviated flowchart of the structure and computational procedure of the modular subroutine ENDCON of the RADONE computer code (continued).

2. Based on the information available to the user, ENDCON reads the set of data (Sect. 7.6) for the user-specified control conditions at the upstream end of the main flow channel (Sect. 4.3). The specified set of input data for the control parameters associated with the user-specified control conditions (Sect. 4.3) includes IUPCRW, CRWMNU, CRWMXU, IUPCRB, CRBMNU, and CRBMXU (Sect. 7.6), which are required for specifying the minimum limits and the maximum limits of the temporal variations of the radionuclide concentration conditions at the upstream end of the main flow channel.

ORNL DWG 84 14076

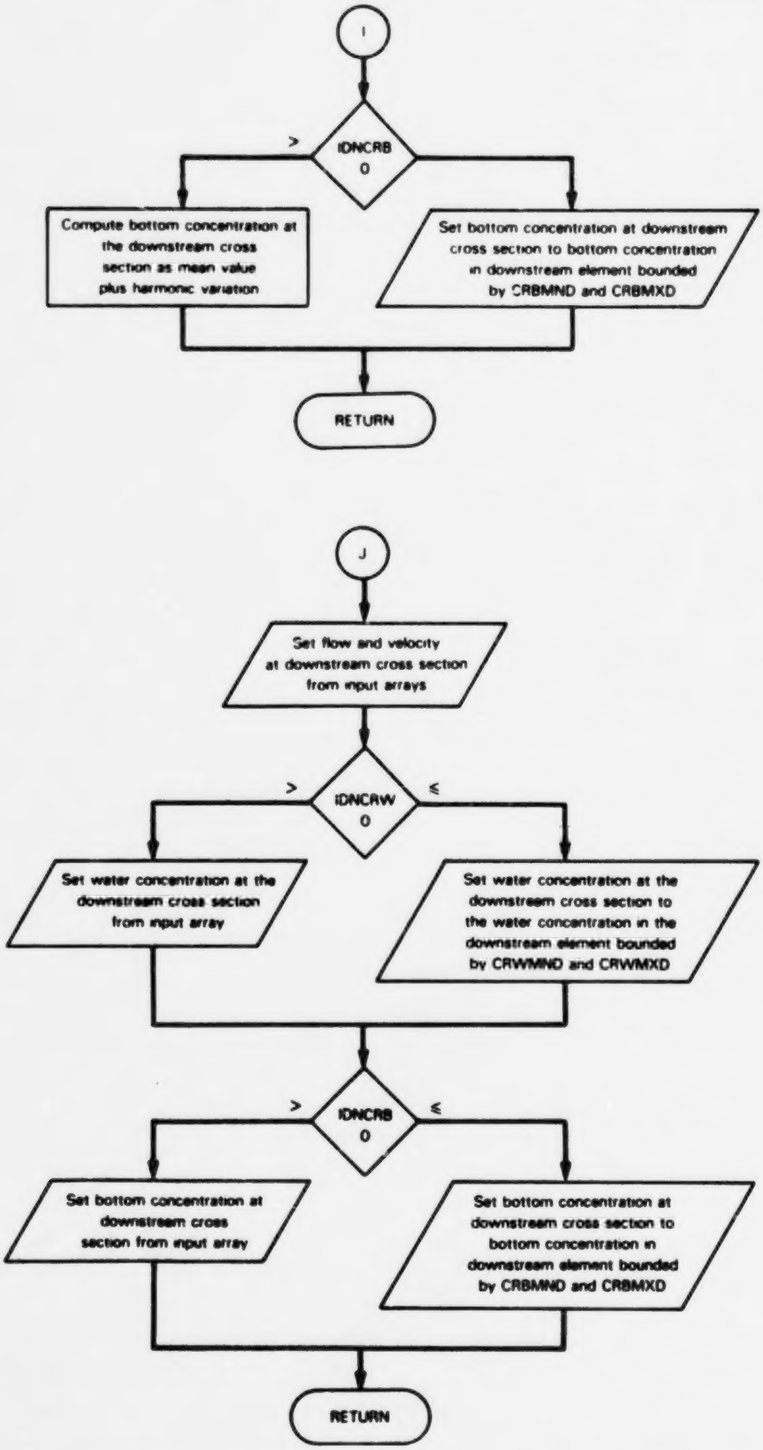
I
>
IDNCRB
0
Compute bottom concentration at the downstream cross section as mean value plus harmonic variation
Set bottom concentration at downstream cross section to bottom concentration in downstream element bounded by CRBMND and CRBMXD
RETURN
J
Set flow and velocity at downstream cross section from input arrays
>
IDNCRW
0
≤
Set water concentration at the downstream cross section from input array
Set water concentration at the downstream cross section to the water concentration in the downstream element bounded by CRWMND and CRWMXD
>
IDNCRB
0
≤
Set bottom concentration at downstream cross section from input array
Set bottom concentration at downstream cross section to bottom concentration in downstream element bounded by CRBMND and CRBMXD
RETURN

Fig. 6.6f. Abbreviated flowchart of the structure and computational procedure of the modular subroutine ENDCON of the RADONE computer code (continued).

3. Similarly, based on the information available to the user, ENDCON reads the set of data (Sect. 7.6) for the user-specified control conditions at the downstream end of the main flow channel (Sect. 4.3). The specified set of input data for the control parameters, associated with the user-specified control conditions (Sect. 4.3), includes IDNCRW, CRWMND, CRWMXD, IDNCRB, CRBMND, and CRBMXD (Sect. 7.6), which are required for specifying the allowable minimum limits and the allowable maximum limits of the temporal variations of the radionuclide concentration conditions at the downstream end of the main flow channel.

The second part of the preparation stage of ENDCON reads the specified input data for the detailed flow and radionuclide concentration conditions at the upstream end, for one of the two user-specified cases, controlled-flow dam conditions or tidal flow conditions, depending on the specified value of the integer control parameter IUPCON. For IUPCON = 0, which indicates the user-specified case for simple closed-dam conditions at the upstream end, ENDCON does not require any additional data for flow and radionuclide concentration conditions at the upstream end (Sect. 4.3.1). However, for the user-specified cases for controlled-flow dam conditions or tidal flow conditions at the upstream end, ENDCON requires additional sets of input data for specifying the temporal variations (or temporally uniform conditions) of the principal solution variables at the upstream-end enclosure surface of the main flow channel.

For the value of the integer control parameter IUPCON = 1, which indicates the user-specified case for controlled-flow dam conditions, ENDCON initiates and completes the reading of the detailed specified input data for upstream-end conditions (Sect. 4.3.2) according to the following two operational steps (Fig. 6.6a):

4. ENDCON reads the specified input data for the number of time periods NUPPER (Sect. 7.6) that will be used for specifying the temporal variations (or temporally uniform conditions) of the principal solution variables at the upstream end of the main flow channel. At least one time period (i.e., NUPPER $\geq$ 1) is required for specifying controlled-flow dam conditions at the upstream end.
5. ENDCON reads and stores in the labeled COMMON/ENDPER/ (Appendix A) the specified set of input data, as IPER = 1, ..., NUPPER list of records (Sect. 7.6), for the duration of the specified time periods (Sect. 4.3.2) and the detailed conditions for the principal solution variables at the upstream end of the main flow channel. The set of specified input data for the time periods and the flow and radionuclide concentration conditions (Sect. 4.3) include TPRUPR(IPER), GFLUPR(IPER), VLXUPR(IPER), CRWUPR(IPER), and CRBUPR(IPER) (Sect. 7.6), which are required for specifying the temporal variations of the controlled-flow dam conditions at the upstream end of the main flow channel.

It is important that extensive specified input data sets associated with the user-specified case for controlled-flow dam conditions at the upstream end of the main flow channel are required only for long-term and accurate representations of the temporal variations of principal solution variables at the upstream end and for obtaining the long-term and accurate computer simulations of flow conditions in a controlled river and/or a tidal estuary. For temporally uniform upstream-end conditions associated with the user-specified case for controlled-flow dam conditions, only a single-record specified input data set, with IPER = NUPPER = 1, would be sufficient to represent the temporally uniform conditions for principal solution variables at the upstream end of the main flow channel (Sect. 7.6). Furthermore, if the necessary information for specifying (1) upstream-end channel flow velocity VLXUPS, (2) upstream-end water concentration of the radionuclide in the water layer CRWUPS, and/or (3) upstream-end bottom concentration of the radionuclide in the bottom layer CRBUPS is not available to the user, the allocated spaces on the data records can be left blank in the preparation of the specified input data sets for the controlled-flow dam conditions. Hence, with the specified control conditions at the upstream-end, consisting of IUPCRW = 0 and IUPCRB = 0, for the radionuclide concentration conditions, the computation stage of ENDCON first assumes that the channel flow velocity at the upstream end is zero, VLXUPS = 0; then, it determines internally the water concentration of the radionuclide in the water layer [Eqs. (4.36b) and (4.36c)] and/or bottom concentration of the radionuclide in the bottom layer [Eqs. (4.38b) and (4.38c)] at the upstream end, based on the user-specified minimum allowable water concentration of the radionuclide in the water layer CRWMNU or maximum allowable water concentration of the radionuclide in the water layer CRWMXU and/or on the user-specified minimum allowable bottom concentration of the radionuclide in the bottom layer CRBMNU or maximum allowable bottom concentration of the radionuclide in the bottom layer CRBMXU (Sect. 7.6), without requiring any additional input data, for the flow and radionuclide concentration conditions at the upstream controlled-flow dam end of the main flow channel.

For the value of the integer control parameter IUPCON = 2, which indicates the user-specified case for tidal flow conditions, ENDCON initiates and completes the reading of the specified input data for the upstream-end conditions (Sect. 4.3.3) according to the following three operational steps (Fig. 6.6a):

6. ENDCON reads the specified input data (Sect. 7.6) for the long-term temporal variations of the tidal water-surface elevation conditions (Sect. 4.3.3), consisting of NHRTUP, NVRTUP, and HSRTUP (Sect. 7.6) at the upstream coastal open end of the main flow channel.
7. ENDCON reads and stores in the labeled COMMON/TIDATA/ (Appendix A) the specified set of input data, as IHRT = 1, ..., NHRTUP list of records (Sect. 7.6), for the specified tidal harmonic conditions (Sect. 4.3.3), consisting of TIDTUP(IHRT), TLGTUP(IHRT), and DHBTUP(IHRT) (Sect. 7.6) at the upstream coastal open end of the main flow channel.
8. ENDCON reads and stores in the labeled COMMON/TIDATA/ (Appendix A) the specified set of input data, as IVRT = 1, ..., NVRTUP list of records (Sect. 7.6), for the specified detailed nonharmonic, long-term variations of the principal solution variables (Sect. 4.3.3), consisting of PERTUP(IVRT), DHSRUP(IVRT), CRWMUP(IVRT), DCRWUP(IVRT), CRBMUP(IVRT), and DCRBUP(IVRT) (Sect. 7.6) at the upstream coastal open end of the main flow channel.

It is again important that extensive specified input data sets associated with the user-specified case for tidal flow conditions at the upstream end of the main flow channel are required only for long-term and accurate representations of the temporal variations of principal solution variables in the coastal region at the upstream coastal open end for obtaining long-term and accurate computer simulations of flow conditions in a tidal estuary. For simplified tidal flow conditions at the upstream coastal open end, a single-record specified input data set with IHRT = NHRTUP = 1 would be sufficient to represent single-harmonic variations in the coastal region at the upstream coastal open end of the main flow channel. Also, for long-term, temporally uniform (excluding harmonic variations), upstream-end conditions associated with the user-specified case for tidal flow conditions, again, a single-record specified input data set with IVRT = NVRTUP = 1 would be sufficient to represent the long-term temporally uniform conditions (excluding harmonic variations for the principal solution variables in the coastal region at the upstream coastal open end of the main flow channel (Sect. 7.6). Furthermore, if the necessary information for specifying (1) upstream-end water concentration of the radionuclide in the water layer CRWUPS and/or (2) upstream-end bottom concentration of the radionuclide in the bottom layer CRBUPS is not available to the user, the allocated spaces on the data records can again be left blank in the preparation of the specified input data sets for the case of tidal flow conditions. Hence, with the specified control conditions at the upstream end, consisting of IUPCRW = 0 and IUPCRB = 0, the computation stage of ENDCON again determines internally the water concentration of the radionuclide in the water layer [Eqs. (4.36a)–(4.36c)] and/or bottom concentration of the radionuclide in the bottom layer [Eqs. (4.38a)–(4.38c)] at the upstream end, based on the user-specified minimum allowable water concentration of the radionuclide in the water layer CRWMNU or maximum allowable water concentration of the radionuclide in the water layer CRWMXU and/or on the user-specified minimum allowable bottom concentration of the radionuclide in the bottom layer CRBMNU or maximum allowable bottom concentration of the radionuclide in the bottom layer CRBMXU (Sect. 7.6), without requiring any additional input data, for the flow and radionuclide concentration conditions at the upstream coastal open end of the main flow channel.

The third part of the preparation stage of ENDCON reads the specified input data for the detailed flow and radionuclide concentration conditions at the downstream end, for one of the two user-specified cases, controlled-flow dam conditions or tidal flow conditions, depending on the specified value of the integer control parameter IDNCON. For IDNCON = 0, which indicates the user-specified case for simple closed-dam conditions at the downstream end, ENDCON does not require any additional data for flow and radionuclide concentration conditions at the downstream end (Sect. 4.3.1). However, for the user-specified cases for controlled-flow dam conditions or tidal flow conditions at the downstream end, ENDCON requires additional sets of input data for specifying the temporal variations (or temporally uniform conditions) of the principal solution variables at the downstream-end enclosure surface of the main flow channel.

For the value of the integer control parameter IDNCON = 1, which indicates the user-specified case for controlled-flow dam conditions, ENDCON initiates and completes the reading of the detailed specified input data for the downstream-end conditions (Sect. 4.3.2), according to the following two operational steps (Fig. 6.6b):

9. ENDCON reads the specified input data for the number of time periods NDNPER (Sect. 7.6) that will be used for specifying the temporal variations (or temporally uniform conditions) of the principal solution variables at the downstream end of the main flow channel. At least one time period (i.e., NDNPER ≥ 1) is required for specifying the controlled-flow dam conditions at the downstream end.
10. ENDCON reads and stores in labeled COMMON/ENDPER/ (Appendix A) the specified set of input data, as IPER = 1, ..., NDNPER list of records (Sect. 7.6), for the specified durations of the time periods (Sect. 4.3.2) and the detailed conditions for the principal flow variables at the downstream end of the main flow channel. The set of specified input data for the time periods and the flow and radionuclide concentration conditions (Sect. 4.3) includes TPRDNR(IPER), GFLDNR(IPER), VLXDNR(IPER), CRWDNR(IPER), and CRBDNR(IPER) (Sect. 7.6), which are required for specifying the temporal variations of the controlled-flow dam conditions at the downstream end of the main flow channel.

Again, similar to the specified input data for the controlled-flow dam upstream-end conditions, for temporally uniform conditions, based on limited available information, a simple set of specified input data for the controlled-flow dam conditions can be easily provided as input data by leaving blank the allocated spaces on the data records to indicate VLXDNS = 0, IDNCRW = 0, and IDNCRB = 0 and without any additional input data, for simple controlled-flow dam conditions at the downstream end of the main flow channel.

For the value of the integer control parameter IDNCON = 2, which indicates the user-specified case for tidal flow conditions, ENDCON initiates and completes the reading of the specified input data for downstream-end conditions (Sect. 4.3.3) according to the following three operational steps (Fig. 6.6b):

11. ENDCON reads the specified input data (Sect. 7.6) for the long-term temporal variations of the tidal water-surface elevation conditions (Sect. 4.3.3), consisting of NHRTDN, NVRTDN, and HSRTDN (Sect. 7.6), at the downstream coastal open end of the main flow channel.
12. ENDCON reads and stores in the labeled COMMON/TIDATA/ (Appendix A) the specified set of input data, as IHRT = 1, ..., NHRTDN list of records (Sect. 7.6), for the specified tidal harmonic conditions (Sect. 4.3.3), consisting of TIDTDN(IHRT), TLGTDN(IHRT), and DHTDN(IHRT) (Sect. 7.6) at the downstream coastal open end of the main flow channel.
13. ENDCON reads and stores in the labeled COMMON/TIDATA/ (Appendix A) the specified set of input data, as IVRT = 1, ..., NVRTDN list of records (Sect. 7.6), for the specified detailed harmonic, long-term variations of the principal solution variables (Sect. 4.3.3), consisting of PERTDN(IVRT), DHSRDN(IVRT), CRWMDN(IVRT), DCRWDN(IVRT), CRBMDN(IVRT), and DCRBDN(IVRT) (Sect. 7.6) at the downstream coastal open end of the main flow channel.

Again, similar to the specified input data for the tidal flow conditions at the upstream coastal open end, with only limited available information, a simple set of specified input data for the tidal flow conditions can be easily provided as input data, by leaving blank the allocated spaces on the data records to indicate IDNCRW = 0 and IDNCRB = 0, and without any additional input data, for the tidal flow conditions at the downstream coastal open end of the main flow channel.

The fourth part of the preparation stage of the modular subroutine ENDCON consists of the following operational step (Fig. 6.6b):

14. For the value of the integer control parameter IWRITE = 1, which is read in the MAIN program (Sect. 6.2) and passed through the labeled COMMON/PUTOUT/, ENDCON writes as printed output (Sect. 8.6) all the specified input data, according to the user-specified cases for (a) simple closed-dam conditions, (b) controlled-flow dam conditions, or (c) tidal flow conditions, for specifying the temporal variations (or temporally uniform conditions) of the principal solution variables at the upstream-end enclosure surface and at the downstream-end enclosure surface of the main flow channel (Sects. 4.3.1–4.3.4).

The fifth part of the preparation stage of ENDCON includes one of the special features that enable the user to implement RADONE with a minimal amount of effort in simulating accurately the detailed flow and radionuclide concentration conditions in an actual controlled river or tidal estuary, based on extensive specified input data for upstream-end and downstream-end conditions of the main flow channel. The structure and computational procedure of ENDCON include special provisions for aligning the time periods of the specified input data for the temporal variations of the principal solution variables at the upstream end and at the downstream end of the main flow channel (Sects. 4.3.1–4.3.4 and 7.6) with the internally calculated time levels of the solution according to the general computational algorithm of RADONE. Hence, if the user already has extensive sets of specified input data for upstream-end and downstream-end conditions for a long overall period (e.g., 1 week, 1 month, and 1 year), with a large number of time periods (Sect. 4.3) for representing the short-term variations (e.g., 1 h or 1 d) of the principal solution variables, the computer simulations with RADONE can be started at any time within the overall period of the available data, without requiring any modification of the extensive sets of specified input data. The internal computational algorithm of the preparation stage of ENDCON automatically aligns the specified initial time (Sect. 6.4) with the appropriate specified time periods of the specified input data for upstream-end and downstream-end conditions of the main flow channel.

The fifth part of the preparation stage of ENDCON initiates and completes the necessary procedure for determining the appropriate time periods and the specified input data for upstream-end and downstream-end conditions that correspond to the specified initial time (Sect. 6.4), according to the following four operational steps (Fig. 6.6b):

15. For the value of the integer control parameter IUPCON = 1, which indicates the user-specified case for controlled-flow dam conditions at the upstream end of the main flow channel, and with the specified initial time T, which is read in the modular subroutine INITAL (Sect. 6.4) and which is passed through the labeled COMMON/CONTRL/, ENDCON determines the appropriate specified time period for upstream-end conditions TPRUPR(IPER), which includes the specified initial time T, and sets the detailed conditions for principal flow variables at the upstream end of the main flow channel. ENDCON assigns the unstored values for the parameters representing the controlled-flow dam conditions to the corresponding values of specified input data, as GFLUPS = GFLUPR(IPER), VLXUPS = VLXUPR(IPER), CRWUPS = CRWUPR(IPER), and CRBUPS = CRBUPR(IPER), during the specified time periods TPRUPR(IPER), for IPE = 1, ..., NUPPER, which contains the initial time T.
16. For the value of the integer control parameter IUPCON = 2, which indicates the user-specified case for tidal flow conditions at the upstream end of the main flow channel, and with the specified initial time T, which is read in the modular subroutine INITAL (Sect. 6.4) and passed through the labeled COMMON/CONTRL/, ENDCON determines the appropriate specified time period for upstream-end conditions PERTUP(IVRT), which includes the specified initial time T, and sets the values for the detailed, nonharmonic, long-term variations of the principal solution variables at the upstream end of the main flow channel. ENDCON assigns the unstored values for the parameters representing tidal flow conditions, with long-term variations (excluding harmonic variations), to the corresponding values of specified input data, as CRWUPM = CRWMUP(IVRT), DUPCRW = DCRWUP(IVRT), CRBUPM = CRBMUP(IVRT), and DUPCRB = DCRBUP(IVRT), during the specified time period PERTUP(IVRT), for IVRT = 1, ..., NVRTUP, which contains the initial time T.
17. For the value of the integer control parameter IDNCON = 1, which indicates the user-specified case for controlled-flow dam conditions at the downstream end of the main flow channel, and with the specified initial time T, which is read in the modular subroutine INITAL (Sect. 6.4) and passed through the labeled COMMON/CONTRL/, ENDCON determines the appropriate specified time period for downstream-end conditions TPRDNR(IPER), which includes the specified initial time T, and sets the detailed conditions for the principal solution variables at the downstream end of the main flow channel. ENDCON assigns the unstored values for the parameters representing the controlled-flow dam conditions to the corresponding values of specified input data, as GFLDNS = GFLDNR(IPER), BLXDNS = VLXDNR(IPER), CRWDNS = CRWDNR(IPER), and CRBDNS = CRBDNR(IPER), during the specified time period TPRDNR(IPER), for IPER = 1, ..., NDNPER, which contains the initial time T.
18. For the value of the integer control parameter IDNCON = 2, which indicates the user-specified case for tidal flow conditions at the downstream end of the main flow channel, and with the specified initial time T, which is read in the modular subroutine INITAL (Sect. 6.4) and passed through the labeled COMMON/CONTRL/, ENDCON determines the appropriate specified time period for downstream-end conditions PERTDN(IVRT), which includes the specified initial time T, and sets the values for the detailed, nonharmonic, long-term variations of the principal solution variables at the downstream end of the main flow channel. ENDCON assigns the unstored values for the parameters representing the tidal

flow conditions, with long-term variations (excluding harmonic variations), to the corresponding values of specified input data, as CRWDNM = CRWMDN(IVRT), DDNCRW = DCRWDN(IVRT), CRBDNM = CRBMDN(IVRT), and DDCRB = DCRBDN(IVRT), during the specified time period PERTDN(IVRT), for IVRT = 1, ..., NVRTDN, which contains the initial time T.

At the end of the preparation stage, ENDCON completes all necessary initialization procedures that would be required in the subsequent computation stage of the subroutine; then, it returns to the MAIN program.

6.6.2 Computation Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of RADONE, ENDCON is called (1) by the modular subroutine SOLVER (Sect. 6.5) at every intermediate time level T of the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5) and (2) by the modular subroutine OUTPUT (Sect. 6.13), which writes the computed results for the principal flow variables after each NTW time step (Sect. 6.2).

The first part of the computation stage of ENDCON calculates, based on specified input data, upstream-end conditions for the principal solution variables according to one of the three user-specified cases: (1) simple closed-dam conditions (Sect. 4.3.1), (2) controlled-flow dam conditions (Sect. 4.3.2), and (3) tidal flow conditions (Sect. 4.3.3).

For the value of the integer control parameter IUPCON = 0, which indicates the user-specified case for simple closed-dam conditions (Sect. 4.3.1), ENDCON initiates and completes the calculations of upstream-end conditions for the principal solution variables, according to the following three operational steps (Fig. 6.6c):

1. ENDCON determines, at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, the upstream-end water surface elevation HSRUPS, based on linear extrapolation from the values of the water surface elevation at the upstream-end element HSR(1) and the water surface elevation in the adjacent internal element HSR(2) [Eq. (4.2)].
2. ENDCON sets equal to zero, at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, (a) the upstream-end channel flow rate GFLUPS = 0 [Eq. (4.4)] and (b) the upstream-end channel flow velocity VLXUPS = 0 [Eq. (4.5)].
3. ENDCON determines, at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, (a) the upstream-end water concentration of the radionuclide in the water layer CRWUPS as equal to the water concentration of the radionuclide in the water layer in the upstream-end element CRW(1) [Eq. (4.8)] and (b) the upstream-end bottom concentration of the radionuclide in the bottom layer CRBUPS as equal to the bottom concentration of the radionuclide in the bottom layer in the upstream-end element CRB(1) [Eq. (4.9)].

For the value of the integer control parameter IUPCON = 1, which indicates the user-specified case for controlled-flow dam conditions (Sect. 4.3.2), ENDCON initiates and completes the calculations of the upstream-end conditions of the principal solution variables according to the following five operational steps (Fig. 6.6d):

4. Based on the value of the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, ENDCON determines the appropriate specified time period for the

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specified upstream-end conditions TPRUPR(IPER). This is accomplished either (a) by retaining the already determined specified time period for the upstream-end conditions TPRUPR(IPER), if it includes the intermediate time level T, or (b) if the already determined specified time period for the upstream-end conditions TPRUPR(IPER) does not include the intermediate time level T, by advancing IPER by 1 until the advanced specified time period for the upstream-end conditions TPRUPR(IPER+1) includes the intermediate time level T, for IPER = 1, ..., NUPPER. If the intermediate time level T extends beyond the specified time corresponding to the end of the last input record for the specified time period TPRUPR(NUPPER), ENDCON automatically retains the last specified time period TPRUPR(NUPPER); and it determines the upstream-end conditions for the principal solution variables based on the specified input data for the last specified time period TPRUPR(NUPPER).

5. ENDCON assigns (a) the upstream-end channel flow rate GFLUPS = GFLUPR(IPER) as the specified upstream-end channel flow rate [Eq. (4.18)] during the specified time period TPRUPR(IPER) and (b) the upstream-end channel flow velocity VLXUPS = VLXUPR(IPER) as the specified upstream-end channel flow velocity [Eq. (4.19)] during the specified time period TPRUPR(IPER), for IPER = 1, ..., NUPPER.

6a. For the control condition at the upstream end IUPCRW = 0, as the specified value of the integer control parameter for internally determining the water concentration of the radionuclide in the water layer at the upstream-end enclosure surface [Eqs. (4.36a)-(4.36c)], ENDCON determines the upstream-end water concentration of the radionuclide in the water layer (1) by first assuming that the upstream-end water concentration of the radionuclide in the water layer CRWUPS = CRW(1) as the water concentration of the radionuclide in the water layer in the upstream element IX = 1 [Eq. (4.36a)] and (2) by considering the user-specified values for the minimum allowable water concentration of the radionuclide in the water layer at the upstream end CRWMNU [Eq. (4.36b)] and the maximum allowable water concentration of the radionuclide in the water layer at the upstream end CRWMXU [Eq. (4.36c)].

6b. For the control condition at the upstream end IUPCRW = 1, as the specified value of the integer control parameter for determining the water concentration of the radionuclide in the water layer at the upstream-end enclosure surface based on specified input data, ENDCON assigns directly the upstream-end water concentration of the radionuclide in the water layer CRWUPS = CRWUPR(IPER) as the specified upstream-end water concentration of the radionuclide in the water layer [Eq. (4.22)], during the specified time period TPRUPR(IPER) for IPER = 1, ..., NUPPER.

7a. For the control condition at the upstream end IUPCRB = 0, as the specified value of the integer control parameter for internally determining the bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface [Eqs. (4.38a) and (4.38b)], ENDCON determines the upstream-end bottom concentration of the radionuclide in the bottom layer (1) by first assuming that the upstream-end bottom concentration of the radionuclide in the bottom layer CRBUPS = CRB(1) as the bottom concentration of the radionuclide in the bottom layer in the upstream element IX = 1 [Eq. (4.38a)] and (2) by considering the user-specified values for the minimum allowable bottom concentration of the radionuclide in the bottom layer at the upstream end CRBMNU [Eq. (4.38b)] and the maximum allowable bottom concentration of the radionuclide in the bottom layer at the upstream end CRBMXU [Eq. (4.38c)].

7b. For the control condition at the upstream end IUPCRB = 1, as the specified value of the integer control parameter for determining the bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface based on specified input data, ENDCON assigns directly the upstream-end bottom concentration of the radionuclide in the bottom layer CRBUPS = CRBUPR(IPER) as the specified upstream-end bottom concentration of the radionuclide in the bottom layer [Eq. (4.24)], during the specified time period TPRUPR(IPER), for IPER = 1, ..., NUPPER.

8. ENDCON determines, at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, the upstream-end water surface elevation HSRUPS, based on linear extrapolation from the values of the water surface elevation at the upstream-end element HSR(1) and the water surface elevation in the adjacent internal element HSR(2) [Eq. (4.2)].

For the value of the integer control parameter IUPCON = 2, which indicates the user-specified case for tidal flow conditions (Sect. 4.3.3), ENDCON initiates and completes the calculations of the upstream-end conditions of the principal solution variables according to the following six operational steps (Figs. 6.6c and 6.6d):

9. Based on the value of the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, ENDCON determines the appropriate specified time period for the specified detailed, nonharmonic, long-term, temporal variations of the principal solution variables at the upstream coastal open end PERTUP(IVRT). This is accomplished either (a) by retaining the already determined specified time period for the upstream coastal open end conditions PERTUP(IVRT), if it includes the intermediate time level T, or (b) if the already determined specified time period for the upstream coastal open end conditions PERTUP(IVRT) does not include the intermediate time level T, by advancing IVRT by 1 until the advanced specified time period for the upstream coastal open-end conditions PERTUP(IVRT+1) includes the intermediate time level T, for IVRT = 1, ..., NVRTUP.

If the intermediate time level T extends beyond the specified time corresponding to the end of the last input record for the specified time period for the upstream coastal open end conditions PERTUP(NVRTUP), ENDCON automatically retains the last specified time period for the upstream coastal open end conditions PERTUP(NVRTUP); and it determines the specified detailed, nonharmonic long-term, temporal variations of the principal flow variables at the upstream coastal open end based on specified input data for the last specified time period for upstream coastal open end conditions PERTUP(NVRTUP).

10. ENDCON calculates water surface elevation at the upstream coastal open end HSRTUP at the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, based on the specified input data for NHRTUP number of harmonics as the sum of the NHRTUP number of cosine harmonic variations [Eq. (4.26)]. These specified input data for NHRTUP number of harmonics consist of (a) TIDTUP(IHRT) as the specified period of the IHRT harmonic of the upstream-end tidal variation of water surface elevation at the upstream coastal open end, (b) TLGTUP(IHRT) as the specified lag time (relative to midnight) of the IHRT harmonic of the upstream-end tidal variation of water surface elevation at the upstream coastal open end, and (c) DHBTUP(IHRT) as the specified amplitude of the IHRT harmonic of the upstream-end tidal variation of water surface elevation at the upstream coastal open end.
11. ENDCON determines, at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, the upstream-end channel flow rate GFLUPS, based on linear extrapolation from the values of channel flow rate in the upstream-end half-element GFX(1) and channel flow rate in the adjacent half-element GFX(2) [Eq. (4.28)].

12. ENDCON determines, at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, the upstream-end channel flow velocity VLXUPS by dividing the already calculated value of the upstream-end channel flow rate GFLUPS by the cross-sectional area of the upstream-end enclosure surface ACC(1), which is calculated in the modular subroutine REGION (Sect. 6.3) and passed to ENDCON through the labeled COMMON/CONTRL/ [Eq. (4.30)].

13a. For the control condition at the upstream end IUPCRW = 0, ENDCON determines the upstream-end water concentration of the radionuclide in the water layer CRWUPS according to the same procedure as outlined in step 6a [Eqs. (4.36a)–(4.36c)].

13b. For the control condition at the upstream end IUPCRW = 1, as the specified value of the integer control parameter for determining the water concentration of the radionuclide in the water layer at the upstream-end enclosure surface based on specified input data, ENDCON calculates the water concentration of the radionuclide in the water layer, in the coastal region at the upstream coastal open end CRWUPS (Appendix A) at the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/. The calculation is based on the specified input data for (1) CRWMUP(IVRT) as the specified upstream-end average water concentration of the radionuclide in the water layer for representing the long-term variation of the mean water concentration of the radionuclide in the water layer (excluding harmonic variations) in the coastal region at the upstream coastal open end [Eq. (4.32)], during the specified time period PERTUP(IVRT), for IVRT = 1, ..., NVRTUP, (2) TIDTUP(1) as the specified period of the first harmonic of the upstream-end tidal variation of the water surface elevation at the upstream coastal open end, (3) TLGTUP(1) as the specified lag time (relative to midnight) of the first harmonic of the tidal variation of water surface elevation at the upstream coastal open end, and (4) DCRWUP(IVRT) as the specified amplitude of the short-term periodic variation of the upstream-end water concentration of the radionuclide in the water layer in the coastal region at the upstream coastal open end [Eq. (4.32)], during the specified time period PERTUP(IVRT), for IVRT = 1, ..., NVRTUP.

14a. For the control condition at the upstream end IUPCRB = 0, ENDCON determines the upstream-end bottom concentration of the radionuclide in the bottom layer CRBUPS, according to the same procedure outlined in step 7a [Eqs. (4.38a)–(4.38c)].

14b. For the control condition at the upstream end IUPCRB = 1, as the specified value of the integer control parameter for determining the bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface based on specified input data, ENDCON calculates the bottom concentration of the radionuclide in the bottom layer, in the coastal region at the upstream coastal open end CRBUPS at the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/. The calculation is based on the specified input data for (1) CRBMUP(IVRT) as the specified upstream-end average bottom concentration of the radionuclide in the bottom layer for representing the long-term variation of the mean bottom concentration of the radionuclide in the bottom layer (excluding harmonic variation) in the coastal region at the upstream coastal open end [Eq. (4.34)], during the specified time period PERTUP(IVRT), for IVRT = 1, ..., NVRTUP, (2) TIDTUP(1) as the specified period of the first harmonic of the upstream-end tidal variation of the water surface elevation at the upstream coastal open end, (3) TLGTUP(1) as the specified lag time (relative to midnight) of the first harmonic of the tidal variation of the water surface elevation at the upstream coastal open end, and (4) DCRBUP(IVRT) as the specified amplitude of the short-term periodic variation of the upstream-end bottom concentration of the radionuclide in the bottom layer in the coastal region at the upstream coastal open end [Eq. (4.34)], during the specified time period PERTUP(IVRT), for IVRT = 1, NVRTUP.

The second part of the computation stage of ENDCON calculates, based on specified input data, downstream-end conditions for the principal flow variables, according to one of three user-specified cases: (1) simple closed-dam conditions (Sect. 4.3.1), (2) controlled-flow dam conditions (Sect. 4.3.2), and (3) tidal flow conditions (Sect. 4.3.3).

For the value of the integer control parameter IDNCON = 0, which indicates the user-specified case for simple closed-dam conditions (Sect. 4.3.1), ENDCON initiates and completes the calculations of downstream-end conditions for the principal solution variables, according to the following three operational steps (Fig. 6.6e):

15. ENDCON determines at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, the downstream-end water surface elevation HSRDNS based on linear extrapolation from the values of water surface elevation in the downstream-end element HSR(NX) and water surface elevation in the adjacent internal element HSR(NX − 1) [Eq. (4.3)].
16. ENDCON sets equal to zero, at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, (a) the downstream-end channel flow rate GFLDNS = 0 [Eq. (4.6)] and (b) the downstream-end channel flow velocity VLXDNS = 0 [Eq. (4.7)].
17. ENDCON determines at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, (a) the downstream-end water concentration of the radionuclide in the water layer CRWDNS as equal to the water concentration of the radionuclide in the water layer in the downstream-end element CRW(NX) [Eq. (4.9)] and (b) the downstream-end bottom concentration of the radionuclide in the bottom layer CRBUPS as equal to the bottom concentration of the radionuclide in the bottom layer in the downstream element CRB(NX) [Eq. (4.10)].

For the value of the integer control parameter IDNCON = 1, which indicates the user-specified case for controlled-flow dam conditions (Sect. 4.3.2), ENDCON initiates and completes calculations of the downstream-end conditions of the principal solution variables according to the following five operational steps (Fig. 6.6f):

18. Based on the value of the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, ENDCON determines the appropriate specified time period for the specified downstream-end conditions TPRDNR(IPER). This is accomplished either (a) by retaining the already determined specified time period for the downstream-end conditions TPRDNR(IPER), if it includes the intermediate time level T, or (b) if the already determined specified time period for the downstream-end conditions TPRDNR(IPER) does not include the intermediate time level T, by advancing IPER by 1 until the advanced specified time period for the downstream-end conditions TPRDNR(IPER + 1) includes the intermediate time level T, for IPER = 1, ..., NDNPER. If the intermediate time level T extends beyond the specified time corresponding to the end of the last input record for the specified time period TPRDNR(NDNPER), ENDCON automatically retains the last specified time period TPRDNR(NDNPER); and it determines the downstream-end conditions for the principal solution variables based on the specified input data for the last specified time period TPRDNR(NDNPER).
19. ENDCON assigns (a) the downstream-end channel flow rate GFLDNS = GFLDNR(IPER) as the specified downstream-end channel flow rate [Eq. (4.20)] during the specified time period

TPRDNR(IPER) and (b) the downstream-end channel flow velocity VLXDNS = VLXDNR(IPER) as the specified downstream-end channel flow velocity [Eq. (4.21)] during the specified time period TPRDNR(IPER), for IPER = 1, ..., NDNPER.

20a. For the control condition at the downstream end IDNCRW = 0, as the specified value of the integer control parameter for internally determining the water concentration of the radionuclide in the water layer at the downstream-end enclosure surface [Eqs. (4.37a)-(4.37c)], ENDCON determines the downstream-end water concentration of the radionuclide in the water layer (1) by first assuming that the downstream-end water concentration of the radionuclide in the water layer CRWDNS = CRW(NX) as the water concentration of the radionuclide in the downstream element IX = NX [Eq. (4.37a)] and (2) by considering the user-specified values for the minimum allowable water concentration of the radionuclide in the water layer at the downstream end CRWMND [Eq. (4.37b)] and the maximum allowable water concentration of the radionuclide in the water layer at the downstream end CRWMXD [Eq. (4.37c)].

20b. For the control condition at the downstream end IDNCRW = 1, as the specified value of the integer control parameter for determining the water concentration of the radionuclide in the water layer at the downstream-end enclosure surface based on specified input data, ENDCON assigns directly the downstream-end water concentration of the radionuclide in the water layer CRWDNS = CRWDNR(IPER) as the specified downstream-end water concentration of the radionuclide in the water layer [Eq. (4.23)], during the specified time period TPRDNR(IPER), for IPER = 1, ..., NDNPER.

21a. For the control condition at the downstream end IDNCRB = 0, as the specified value of the integer control parameter for internally determining the bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface [Eqs. (4.39a)-(4.39c)], ENDCON determines the downstream-end bottom concentration of the radionuclide in the bottom layer (1) by first assuming that the downstream-end bottom concentration of the radionuclide in the bottom layer CRBDNS = CRB(NX) as the bottom concentration of the radionuclide in the bottom layer in the downstream element IX = NX [Eq. (4.39a)] and (2) by considering the user-specified values for the minimum allowable bottom concentration of the radionuclide in the bottom layer at the downstream end CRBMND [Eq. (4.39b)] and the maximum allowable bottom concentration of the radionuclide in the bottom layer at the downstream end CRBMXD [Eq. (4.39c)].

21b. For the control condition at the downstream end IDNCRB = 1, as the specified value of the integer control parameter for determining the bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface based on specified input data, ENDCON assigns directly the downstream-end bottom concentration of the radionuclide in the bottom layer CRBNDS = CRBDNR(IPER) as the specified downstream-end bottom concentration of the radionuclide in the bottom layer [Eq. (4.25)], during the specified time period TPRDNR(IPER), for IPER = 1, ..., NDNPER.

22. ENDCON determines at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, the downstream-end water surface elevation HSRDNS (Appendix A) based on the linear extrapolation from the values of the water surface elevation in the downstream-end element HSR(NX) and the water surface elevation in the adjacent internal element HSR(NX − 1) [Eq. (4.3)].

For the value of the integer control parameter IDNCON = 2, which indicates the user-specified case for tidal flow conditions (Sect. 4.3.3), ENDCON initiates and completes the calculations of the downstream-end conditions of the principal solution variables, according to the following six operational steps (Fig. 6.6f):

23. Based on the value of the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, ENDCON determines the appropriate specified time period for the specified detailed, nonharmonic, long-term temporal variations of the principal solution variables at the downstream coastal open end PERTDN(IVRT). This is accomplished either (a) by retaining the already determined specified time period for the downstream coastal open end conditions PERTDN(IVRT), if it includes the intermediate time level T, or (b) if the already determined specified time period for the downstream coastal open end conditions PERTDN(IVRT) does not include the intermediate time level T, by advancing IVRT by 1 until the advanced specified time period for the downstream coastal open end conditions PERTDN(IVRT + 1) includes the intermediate time level T, for IVRT = 1, ..., NVRTDN. If the intermediate time level T extends beyond the specified time corresponding to the end of the last input records for the specified time period for downstream coastal open end conditions PERTDN(NVRTDN), ENDCON automatically retains the last specified time period for downstream coastal open end conditions PERTDN(NVRTDN); and it determines the specified detailed, nonharmonic, long-term temporal variations of the principal flow variables at the downstream coastal open end based on the specified input data for the last specified time period for the downstream coastal open end conditions PERTDN(NVRTDN).
24. ENDCON calculates water surface elevation at the downstream coastal open end HSRTDN, at the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, based on the specified input data for NHRTDN number of harmonics, as the sum of the NHRTDN number of cosine harmonic variations [Eq. (4.27)]. The specified input data for NHRTDN number of harmonics consist of (a) TIDTDN(IHRT) as the specified period of the IHRT harmonic of the downstream-end tidal variation of water surface elevation at the downstream coastal open end, (b) TLGTDN(IHRT) as the specified lag time (relative to midnight) of the IHRT harmonic of the downstream-end tidal variation of water surface elevation at the downstream coastal open end, and (c) DHBTDN(IHRT) as the specified amplitude of the IHRT harmonic of the downstream-end tidal variation of water surface elevation at the downstream coastal open end.
25. ENDCON determines, at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, the downstream-end channel flow rate GFLDNS, based on the linear extrapolation from the values of channel flow rate in the downstream-end half-element GFX(2*NX) and channel flow rate in the adjacent half-element GFX(2*NX − 1) [Eq. (4.29)].
26. ENDCON determines, at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, the downstream-end channel flow velocity VLXUPS by dividing the already calculated value of the downstream-end channel flow rate GFLDNS by the cross-sectional area of the downstream-end enclosure surface ACC(NC), which is calculated in the modular subroutine REGION (Sect. 6.3) and passed to ENDCON through the labeled COMMON/CONTRL/ [Eq. (4.31)].

27a. For the control condition at the downstream end IDNCRW = 0, ENDCON determines the downstream-end water concentration of the radionuclide in the water layer CRWDNS according to the same procedure as outlined in step 20a [Eqs. (4.37a)–(4.37c)].

27b. For the control condition at the downstream end IDNCRW = 1, as the specified value of the integer control parameter for determining the water concentration of the radionuclide in the water layer at the downstream-end enclosure surface based on specified input data, ENDCON calculates the water concentration of the radionuclide in the water layer, in the coastal region at the downstream coastal open end CRWDNS at the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/. The calculation is based on the specified input data for (1) CRWMDN(IVRT) as the specified downstream-end average water concentration of the radionuclide in the water layer for representing the long-term variation of the mean water concentration of the radionuclide in the water layer (excluding harmonic variations) in the coastal region at the downstream coastal open end [Eq. (4.33)], during the specified time period PERTDN(IVRT), for IVRT = 1, ..., NVRTDN, (2) TIDTDN(1) as the specified period of the first harmonic of the downstream-end tidal variation of water surface elevation at the downstream coastal open end, (3) TLGTDN(1) as the specified lag time (relative to midnight) of the first harmonic of the tidal variation of water surface elevation at the downstream coastal open end, and (4) DCRWDN(IVRT) as the specified amplitude of the short-term periodic variation of the downstream-end water concentration of the radionuclide in the water layer in the coastal region at the downstream coastal open end [Eq. (4.33)], during the specified time period PERTDN(IVRT), for IVRT = 1, ..., NVRTDN.

28a. For the control condition at the downstream end IDNCRB = 0, ENDCON determines the downstream-end bottom concentration of the radionuclide in the bottom layer CRBDNS, according to the same procedure outlined in step 21a [Eqs. (4.39a)–(4.39c)].

28b. For the control condition at the downstream end IDNCRB = 1, as the specified value of the integer control parameter for determining the bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface based on specified input data, ENDCON calculates the bottom concentration of the radionuclide in the bottom layer, in the coastal region at the downstream coastal open end CRBDNS at the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/. The calculation is based on the specified input data for (1) CRBMDN(IVRT) as the specified downstream-end average bottom concentration of the radionuclide in the bottom layer for representing the long-term variation of the mean bottom concentration of the radionuclide in the bottom layer (excluding harmonic variations) in the coastal region at the downstream coastal open end [Eq. (4.35)], during the specified time period PERTDN(IVRT), for IVRT = 1, ..., NVRTDN, (2) TIDTDN(1) as the specified period of the first harmonic of the downstream-end tidal variation of the water surface elevation at the downstream coastal open end, (3) TLGTDN(1) as the specified lag time (relative to midnight) of the first harmonic of the tidal variation of the water surface elevation at the downstream coastal open end, and (4) DCRBDN(IVRT) as the specified amplitude of the short-term periodic variation of the downstream-end bottom concentration of the radionuclide in the bottom layer in the coastal region at the downstream coastal open end [Eq. (4.35)], during the specified time period PERTDN(IVRT), for IVRT = 1, ..., NVRTDN.

At the end of the computation stage, ENDCON completes the calculations and stores, in the labeled COMMON/ENDFLO/, the values of the principal solution variables at the upstream end and at the downstream end of the main flow channel, based on the specified input data for the end conditions. These variables consist of (1) the upstream-end water surface elevation HSRUPS, (2) the upstream-end channel flow rate GFLUPS, (3) the upstream-end channel flow velocity VLXUPS, (4) the upstream-end water concentration of the radionuclide in the water layer CRWUPS, (5) the upstream-end bottom concentration of the radionuclide in the bottom layer CRBUPS, (6) the downstream-end water surface elevation HSRDNS, (7) the downstream-end channel flow rates GFLDNS, (8) the downstream-end channel flow velocity VLXDNS, (9) the downstream-end water concentration of the radionuclide in the water layer CRWDNS, and (10) the downstream-end bottom concentration of the radionuclide in the bottom layer CRBDNS.

It is important to note that the computation stage of ENDCON does not include the general, pseudospatial, second-upwind-differencing technique (Sect. 4.3.5) in the calculations of the values of the principal solution variables at the upstream end and at the downstream end of the main flow channel. The application of the pseudospatial, second-upwind-differencing technique (Sect. 4.3.5) for determining the computational values of all the transportive solution variables, consisting of (1) channel flow velocity and (2) water concentration of the radionuclide in the water layer at the upstream-end enclosure surface and/or at the downstream-end enclosure surface, is automatically included in the general computational algorithm of the modular subroutine CONVEC (Sect 6.7), based on the specified or calculated values of (1) the upstream-end channel flow rate GFLUPS and/or (2) the downstream-end channel flow rate GFLDNS, respectively.

The structure and computational procedure of the modular subroutine ENDCON of the advanced development program version of the RADONE computer code were specifically designed to enable the user to understand, without undue difficulty, (1) the requirements for the preparation of the specified input data and (2) the computational algorithms associated with the formulations of the relatively complex, temporally varying upstream-end and downstream-end conditions that may be encountered in the applications of the computer code for the assessment of the radiological impact of actual accidental radiologic releases into an actual controlled river or a tidal estuary (e.g., Susquehanna River, Hudson River, and Tennessee River), which serves as the receiving water body to the condenser cooling systems of nuclear power plants. Hence, the structure of ENDCON reads and stores all the specified sets of input data for each time period in the structurally separated part associated with the preparation stage of the subroutine. In certain applications of RADONE, continuous, long-term, and accurate simulations of flow conditions in a controlled river or a tidal estuary during a relatively long period (e.g., six months), based on specified sets of input data with relatively high temporal resolution (e.g., 1 d or 1 h), ENDCON could require substantial storage, which could even exceed the storage requirement of the rest of the general computational algorithm of RADONE. Particularly in computer systems operating in an interactive, time-sharing mode, this excess storage requirement of ENDCON could become a problem because excess core storage allocations to the program could also reduce the overall computational speed of the complete system. This problem can (and should) be avoided by considering successive runs of RADONE for shorter simulation periods (e.g., one month) and only with the parts of the specified input data sets required for each particular simulation period. Because RADONE automatically includes the necessary restart capability, through the modular subroutine OUTPUT (Sects. 6.13 and 8.9) and the modular subroutine INITAL (Sects. 6.4 and 7.4), the user can (and should) separate the specified sets of input data, for a relatively long simulation period (e.g., six months) into partial specified sets of input data for relatively shorter simulation periods (e.g., one month) and apply the code successively by restarting the computations for each successive, relatively shorter simulation period.

The "production program" version of RADONE can eliminate the storage requirement for the specified sets of input data, for each specified time period for the upstream-end and downstream-end conditions, by combining the preparation and computation stages into a single computation stage in the modular subroutine ENDCON.

6.7 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE CONVEC

The modular subroutine CONVEC represents the computational algorithm associated with the contribution of convective transport (along the curvilinear longitudinal *x*-axis of the main flow channel) to the solution of the flow conditions and the conditions for water concentration of the radionuclide in the water layer NX number of elements and 2*NX number of half-elements, according to the one-dimensional formulation of the DEM of the RADONE computer code (Sect. 5.2). CONVEC is the first of the eight major modular subroutines that are called by the computational procedure of the modular subroutine SOLVER, according to the sequential computational method [Eqs. (5.23a)–(5.23d)] based on the successive updating scheme, for the calculations of 4*NX number of right-hand-side solution functions, consisting of (1) $[\overline{F}_{CNV}(\overline{H})]_i$ in all N elements [Eqs. (5.6) and (5.23a)], (2) $[\overline{F}_{CNV}(G_x)]_{i-\frac{1}{4}}$ in all N upstream half-elements [Eqs. (5.11) and (5.23b)], (3) $[\overline{F}_{CNV}(G_x)]_{i+\frac{1}{4}}$ in all N downstream half-elements [Eqs. (5.12) and (5.23c)], and (4) $[\overline{F}_{CNV}(\overline{C}_{rw})]_i$ in all N elements [Eqs. (2.5) and (5.23d)].

The general computational algorithm of CONVEC also includes the contribution of the net force effect of hydrostatic pressure (along the curvilinear longitudinal *x*-axis of the main flow channel) based on the differences of water surface elevation conditions in the elements and half-elements [Eqs. (2.2) and (2.3)]. Although the net force effect of the hydrostatic pressure is not associated directly with the convective momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel), the calculations required for the evaluation of the net force effect of the hydrostatic pressure are included in CONVEC for reasons of computational convenience.

The structure and the computational procedure of CONVEC (Figs. 6.7a–6.7c) consist of two operational stages, the preparation stage and the computation stage, which are initiated and completed, depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.7.1 Preparation Stage

The modular subroutine CONVEC is first called from the MAIN program with the value of the integer control parameter KRUN = 0 (Fig. 6.2), which is passed to the subroutine through the labeled COMMON/CONTRL/.

CONVEC does not read any specified input data, and it initiates and completes the preparation stage internally, according to the following operational step (Fig. 6.7a):

1. CONVEC initializes to zero the values of all right-hand-side solution functions (slopes of the solutions of the principal solution variables) in each element (Sect. 5.2). These solution functions consist of
   a. FNCHSR(IX) = 0 as the right-hand-side solution function (slope) for the solution of water surface elevation HSR(IX) in the element IX [Eq. (5.1a)], which is stored in the labeled COMMON/HSRSOL/,
   b. FNCGFX(IMX) = 0 as the right-hand-side solution function (slope) for the solution of channel flow rate GFX(IMX) in the upstream half-element IMX = 2*IX − 1 [Eq. (5.2a)], which is stored in the labeled COMMON/GFXSOL/,
   c. FNCGFX(IPX) = 0 as the right-hand-side solution function (slope) for the solution of channel flow rate GFX(IPX) in the downstream half-element IPX = 2*IX [Eq. (5.3a)], which is stored in the labeled COMMON/GFXSOL/,

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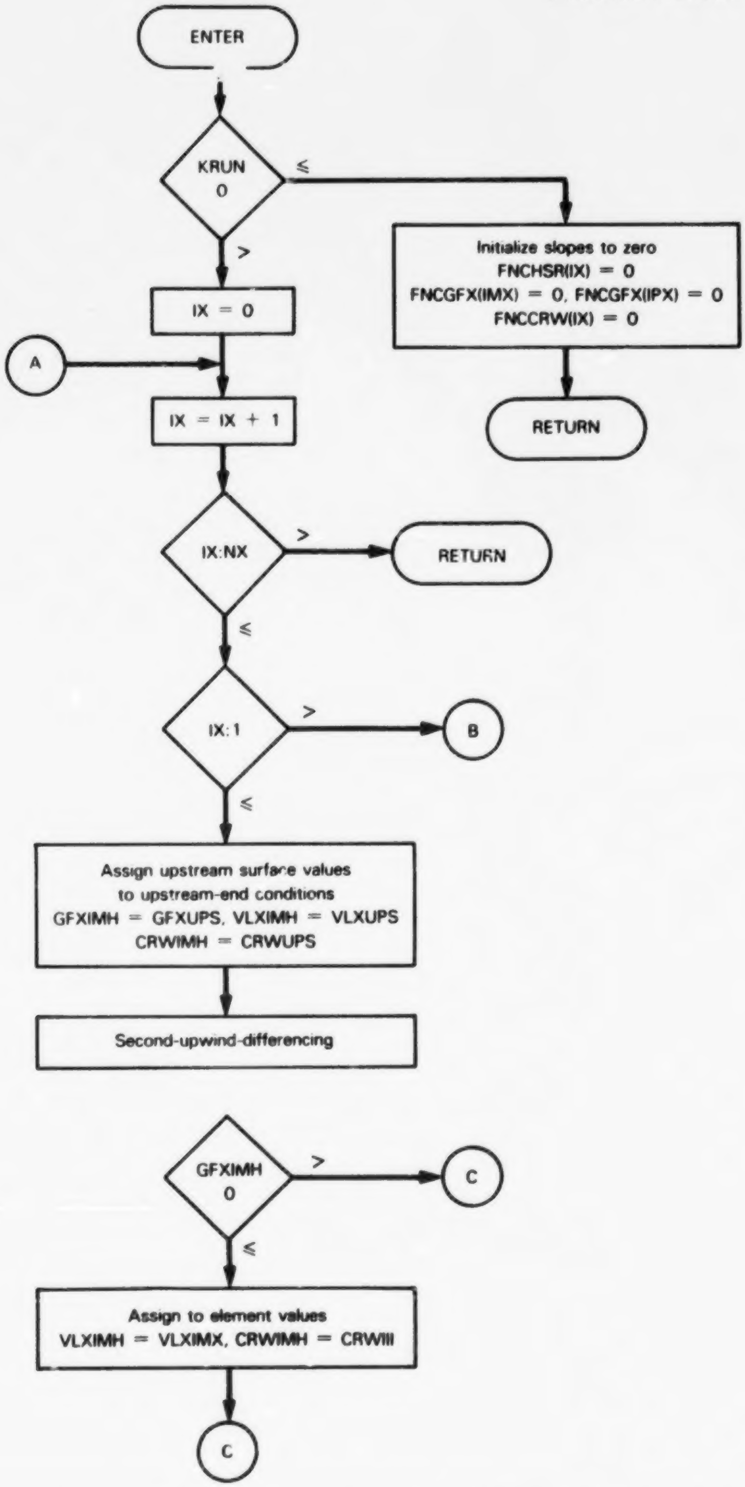
ENTER
KRUN
0
≤
>
Initialize slopes to zero
FNCHSR(IX) = 0
FNCGFX(IMX) = 0, FNCGFX(IPX) = 0
FNCCRW(IX) = 0
RETURN
IX = 0
A
IX = IX + 1
IX:NX
>
RETURN
≤
IX:1
>
B
≤
Assign upstream surface values
to upstream-end conditions
GFXIMH = GFXUPS, VLXIMH = VLXUPS
CRWIMH = CRWUPS
Second-upwind-differencing
GFXIMH
0
>
C
≤
Assign to element values
VLXIMH = VLXIMX, CRWIMH = CRWIII
C

Fig. 6.7a. Abbreviated flowchart of the structure and computational procedure of the modular subroutine CONVEC of the RADONE computer code.

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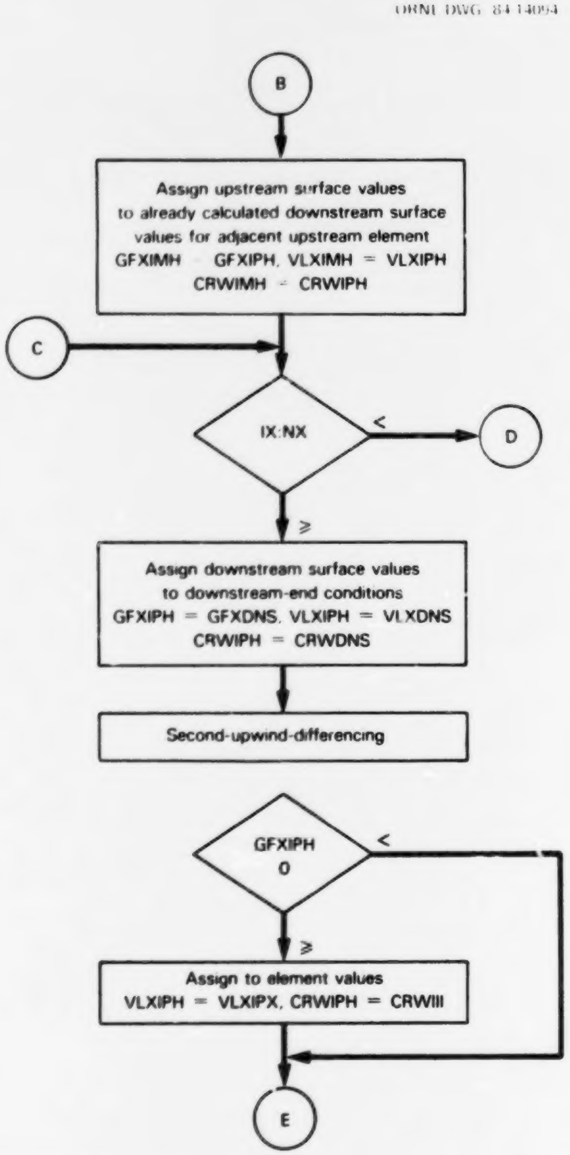
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B
Assign upstream surface values
to already calculated downstream surface
values for adjacent upstream element
GFXIMH = GFXIPH, VLXIMH = VLXIPH
CRWIMH = CRWIPH
C
IX:NX
<
D
≥
Assign downstream surface values
to downstream-end conditions
GFXIPH = GFXDNS, VLXIPH = VLXDNS
CRWIPH = CRWDNS
Second-upwind-differencing
GFXIPH
0
<
≥
Assign to element values
VLXIPH = VLXIPX, CRWIPH = CRWIII
E

Fig. 6.7b. Abbreviated flowchart of the structure and computational procedure of the modular subroutine CONVEC of the RADONE computer code (continued).

d. FNCCRW(IX) = 0 as the right-hand-side solution function (slope) for the solution of water concentration of the radionuclide in the water layer CRW(IX) in element IX [Eq. (5.4a)], which is stored in labeled COMMON/HSRSOL/.

At the end of the preparation stage, CONVEC completes all necessary initialization procedures that would be required in the subsequent computation stage of the subroutine; then, it returns to the MAIN program.

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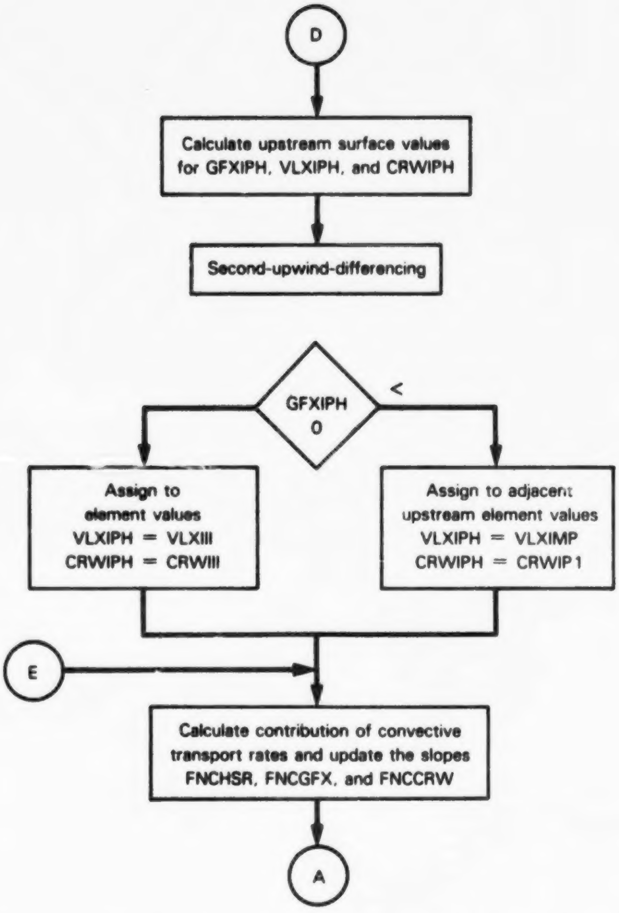
D
Calculate upstream surface values for GFXIPH, VLXIPH, and CRWIPH
Second-upwind-differencing
GFXIPH
0
<
Assign to element values
VLXIPH = VLXIII
CRWIPH = CRWIII
Assign to adjacent upstream element values
VLXIPH = VLXIMP
CRWIPH = CRWIP1
E
Calculate contribution of convective transport rates and update the slopes FNCHSR, FNCGFX, and FNCCRW
A

Fig. 6.7c. Abbreviated flowchart of the structure and computational procedure of the modular subroutine CONVEC of the RADONE computer code (continued).

6.7.2 Computation Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of RADONE, CONVEC is called by the modular subroutine SOLVER (Sect. 6.5) at every intermediate time level T of the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5).

The first part of the computation stage of CONVEC completes the required calculations for the interpolated values of the geometric properties of the main flow channel and the principal flow variables in each element and half-element, according to the following two operational steps (Fig. 6.7a).

1. CONVEC calculates all the linearly interpolated values for the geometric variables of the cross section (Sect. 3.3.1) at five locations in each element, based on already calculated values of HSR(IX),

BSC(IC), and ACC(IC). The five locations in each element are (a) at the upstream enclosure surface of the element at IMH, (b) in the upstream half-element IMX = 2*IX − 1, (c) in the element III = IX, (d) in the downstream half-element IPX = 2*IX, and (e) at the downstream enclosure surface of the element at IPH.

2. CONVEC calculates (a) VLXIMX as channel flow velocity in the upstream half-element IMX, (b) VLXIII as channel flow velocity in the element III(IX), and (c) VLXIPX as channel flow velocity in the downstream half-element IPX, based on already calculated values for GFX(IMX), GFX(IPX), and the values of the cross-sectional areas of the elements.

The second part of the computation stage of CONVEC calculates the values of the principal solution variables at the upstream enclosure surface at IMH of each element IX, according to the following three operational steps (Fig. 6.7a).

For IX = 1, corresponding to the upstream-end element:

3. CONVEC sets the values of the principal flow variables at the upstream enclosure surface at IMH of the upstream-end element IX = 1 equal to the already calculated, in the modular subroutine ENDCON, upstream-end conditions for the principal solution variables (Sect. 6.6), which are passed to the subroutine through the labeled COMMON/ENDFLO/ (Appendix A). These variables consist of
   a. channel flow rate at the upstream enclosure surface GFXIMH = GFLUPS as the upstream-end channel flow rate,
   b. channel flow velocity at the upstream enclosure surface VLXIMH = VLXUPS as the upstream-end channel flow velocity, and
   c. water concentration of the radionuclide in the water layer at the upstream enclosure surface CRWIMH = CRWUPS as the downstream-end water concentration of the radionuclide in the water layer.

4. Based on the direction of the already calculated channel flow rate at the upstream enclosure surface GFXIMH, CONVEC uses the general, pseudospatial, second-upwind-differencing technique to determine the computational values for the transportive intrinsic solution variables (Sects. 3.3.2 and 4.3) at the upstream enclosure surface at IMH of the upstream-end element IX = 1. These variables consist of
   a. VLXIMH as the computational value of channel flow velocity at the upstream enclosure surface [Eqs. (4.38a) and (4.38b)] and
   b. CRWIMH as the computational value of water concentration of the radionuclide in the water layer at the upstream enclosure surface [Eqs. (4.40a) and (4.40b)].

For 1 < IX < NX, corresponding to the internal elements that are not at the downstream end or at the downstream end of the main flow channel:

5. CONVEC transfers directly the already calculated and stored values for the principal solution variables at the downstream enclosure surface at IPH of the upstream adjacent element IX − 1 to the values for the principal flow variables at the upstream enclosure surface at IMH of the element IX. These variables consist of
   a. channel flow rate at the upstream enclosure surface GFXIMH = GFXIPH, which is the already calculated and stored value for channel flow rate at the downstream enclosure surface IPH of the upstream adjacent element IX − 1,

b. channel flow velocity at the upstream enclosure surface VLXIMH = VLXIPH, which is the already calculated and stored value for channel flow velocity at the downstream enclosure surface IPH of the upstream adjacent element IX − 1, and

c. water concentration of the radionuclide in the water layer at the upstream enclosure surface CRWIMH = CRWIPH, which is the already calculated and stored value of water concentration of the radionuclide in the water layer at the downstream enclosure surface IPH of the upstream adjacent element IX − 1.

Hence, the computational procedure of CONVEC eliminates all duplicative calculations associated with interpolation of the principal solution variables at the common enclosure surfaces between the adjacent elements by calculating the values of the principal flow variables only at the downstream enclosure surfaces at IPH of the internal elements.

The third part of the computation stage of CONVEC calculates the values of the principal solution variables at the downstream enclosure surface at IPH of each element IX, according to the following four operational steps (Figs. 6.7b and 6.7c).

For IX = NX, corresponding to the downstream-end element:

6. CONVEC sets the values of the principal flow variables at the downstream enclosure surface at IPH of the downstream-end element IX = NX equal to the already calculated, in the modular subroutine ENDCON, downstream-end conditions for the principal flow variables (Sect. 6.6), which are passed to the subroutine through the labeled COMMON/ENDFLO/ (Appendix A). These variables consist of

   a. channel flow rate at the downstream enclosure surface GFXIPH = GFLDNS as the downstream-end channel flow rate,
   b. channel flow velocity at the downstream enclosure surface VLXIPH = VLXDNS as the downstream-end channel flow velocity, and
   c. water concentration of the radionuclide in the water layer at the downstream enclosure surface CRWIPH = CRWDNS as the downstream-end water concentration of the radionuclide in the water layer.

7. Based on the direction of the already calculated channel flow rate at the downstream enclosure surface GFXIPH, CONVEC uses the general, pseudospatial, second-upwind-differencing technique to determine the computational values for the transportive intrinsic solution variables (Sects. 3.3.2 and 4.3) at the downstream enclosure surface at IPH of the downstream-end element IX = NX. These variables consist of

   a. VLXIPH as the computational value of channel flow velocity at the downstream enclosure surface [Eqs. (4.39a) and (4.39b)] and
   b. CRWIPH as the computational value of water concentration of the radionuclide in the water layer at the downstream enclosure surface [Eqs. (4.41a) and (4.41b)].

For 1 < IX < NX, corresponding to the internal elements that are not at the upstream end or at the downstream end of the main flow channel:

8. CONVEC determines the values of the two principal solution variables, which are required for calculating the second-upwind-differencing interpolated values of the transportive, intrinsic solution variables, at the downstream enclosure surface at IPH of the element IX. The values of the two variables consist of

  a. GFXIPH as the linearly interpolated value of channel flow rate at the downstream enclosure surface at IPH of the element IX [Eq. (3.5c)] and
  b. BLXIMP as the channel flow velocity in the upstream half-element IMP = 2*(IX + 1) − 1 of the downstream adjacent element IX + 1, which is calculated as the channel flow rate GFX [IMP = 2*(IX + 1) − 1] in the upstream half-element IMP = 2*(IX + 1) − 1 of the downstream adjacent element IX + 1 divided by cross-sectional area ARXIMP of the upstream half-element IMP = 2*(IX + 1) − 1 of the downstream adjacent element IX + 1 [Eq. (3.6b)].

9. Based on the direction of the channel flow rate at the downstream enclosure surface GFXIPH, CONVEC uses the general, pseudospatial, second-upwind-differencing technique to determine the computational values for the transportive, intrinsic solution variables (Sect. 3.3.2) at the downstream enclosure surface at IPH of the element IX. These variables consist of

  a. VLXIPH as the computational value channel flow velocity at the downstream enclosure surface at IPH of the element IX [Eqs. (3.11a) and (3.11b)] and
  b. CRWIPH as the computational value of water concentration of the radionuclide in the water layer at the downstream enclosure surface at IPH of the element IX [Eqs. (3.13a) and (3.13b)].

The fourth part of the computation stage of CONVEC calculates the values of channel flow velocity in the element IX, which corresponds to the common enclosure surface between the upstream half-element IMX = 2*IX − 1 and the downstream half-element IPX = 2*IX, according to the following operational step (Figs. 6.7b and 6.7c):

10. Based on the direction of the channel flow rate in the element GFXIII, CONVEC uses the general, pseudospatial, second-upwind-differencing technique to determine the computational value of the transportive, intrinsic channel flow velocity VLXIII in the element IX [Eqs. (3.10a) and (3.10b)].

The fifth part of the computation stage of CONVEC completes the first step of the successive updating scheme [Eqs. (5.23a)–(5.23d)] used in the numerical integration (solution) of the governing computational system of discrete-element equations of the mathematical model (Sect. 5.2) of the RADONE computer code by calculating the terms representing the contribution of convective transport (along the curvilinear longitudinal *x*-axis of the main flow channel) to the right-hand-side solution functions for the solutions of the principal solution variables in each element and in each half-element according to the following four operational steps (Fig. 6.7c):

11. CONVEC calculates, at each intermediate time level T, the part representing convective water mass transport [Eq. (5.23a)] as the value of the right-hand-side solution function (slope) FNCHSR(IX), which is stored in the labeled COMMON/HSRSOL/, for the solution of water surface elevation HSR(IX) in the element IX [Eq. (5.1a)].
12. CONVEC calculates, at each intermediate time level T, the part representing convective momentum transport, which also includes (for reasons of convenience) the net force effect of the hydrostatic pressure [Eq. (5.23b)], as the value of the right-hand-side solution function (slope) FNCGFX(IMX), which is stored in the labeled COMMON/GFXSOL, for the solution of channel flow rate GFX(IMX) in the upstream half-element IMX = 2*IX − 1 [Eq. (5.2a)].
13. CONVEC calculates, at each intermediate time level T, the part representing convective momentum transport, which also includes (for reasons of convenience) the net force effect of the hydrostatic pressure [Eq. (5.23c)], as the value of the right-hand-side solution function (slope) FNCGFX(IPX),

which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IPX) in the downstream half-element IPX = 2*IX [Eq. (5.3a)].

14. CONVEC calculates, at each intermediate time level T, the part representing the convective radionuclide transport [Eq. (5.23d)] as the value of the right-hand-side solution function (slope) FNCCRW(IX), which is stored in the labeled COMMON/CRWSOL/, for the solution of water concentration of the radionuclide in the water layer CRW(IX) in the element IX [Eq. (5.4a)].

At the end of the computation stage, CONVEC completes the calculations, at the intermediate time level T, for all the terms associated with convective transport (along the curvilinear longitudinal *x*-axis of the main flow channel), which represent the first step in the computational construction of all the right-hand-side solution functions for the solutions of the principal flow variables in all the elements and half-elements, according to the successive updating scheme used in the numerical integration (solution) of the governing system of discrete-element equations of the mathematical model (Sect. 5.2) of the RADONE computer code; then, it returns to the modular subroutine SOLVER.

6.8 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE TURBUL

The modular subroutine TURBUL represents the computational algorithm associated with the contribution of nonconvective transport (convection-defect transport and eddy-turbulent transport, along the curvilinear longitudinal *x*-axis of the main flow channel) to the solution of the flow conditions and the conditions for water concentration of the radionuclide in the water layer in the NX number of elements and 2*NX number of half-elements, according to one-dimensional formulation of the DEM of the RADONE computer code (Sects. 3 and 5.2). TURBUL is the second of the eight major modular subroutines that are called by the computational procedure of the modular subroutine SOLVER, according to the sequential computational method [Eqs. (5.2), (5.24a), (5.25b), and (5.24c)] based on the successive updating scheme, for the calculations of 3*NX number of right-hand-side solution functions, consisting of (1) $[\overline{F}_{TRB}(G_x)]_{i-1/4}$ in all N upstream half-elements [Eqs. (5.12) and (5.24a)], (2) $[\overline{F}_{TRB}(\overline{G}_x)]_{i+1/4}$ in all N downstream half-elements [Eqs. (5.18) and (5.24b)], and (3) $[\overline{F}_{TRB}(\overline{C}_{rw})]_i$ in all N elements [Eqs. (2.6) and (5.24c)].

The structure and computational procedure of TURBUL (Figs. 6.8a–6.8g) consist of two operational stages, the preparation stage and the computation stage, which are initiated and completed, depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.8.1 Preparation Stage

The modular subroutine TURBUL is first called from the MAIN program with the value of the integer control parameter KRUN = 0 (Fig. 6.2), which is passed to the subroutine through the labeled COMMON/CONTRL/.

TURBUL initiates and completes the first part of the preparation stage according to the following two operational steps (Fig. 6.8a):

1. TURBUL internally specifies the constant minimum diffusion coefficient as ERDMOL = 0.06 (as $\epsilon_{rw,\min}$ for radionuclide transport in the water layer), including as a part the molecular diffusion coefficient, associated with molecular radionuclide transport [Eqs. (3.64), (3.67), and (3.69)].

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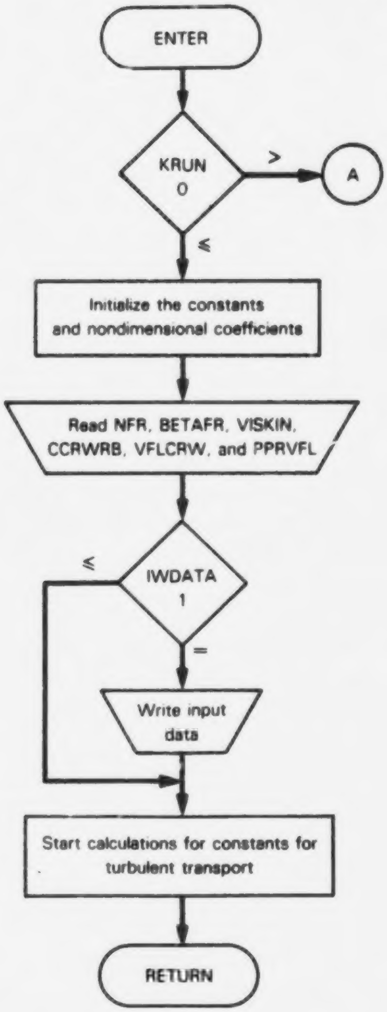
ENTER
KRUN
0
>
A
≤
Initialize the constants and nondimensional coefficients
Read NFR, BETAFR, VISKIN, CCRWRB, VFLCRW, and PPRVFL
≤
IWDATA
1
=
Write input data
Start calculations for constants for turbulent transport
RETURN

Fig. 6.8a. Abbreviated flowchart of the structure and computational procedure of the modular subroutine TURBUL of the RADONE computer code.

2. TURBUL initializes to zero and stores in labeled COMMON/TRBCON/ all the dimensionless coefficients and parameters required for the calculations of the effects of vertical variations of the channel flow velocity and radionuclide concentrations. These coefficients and parameters consist of

   a. CC1DCT(IX) = 0 as the first coefficient associated with the effect of the detailed geometric properties of the cross section of the main flow channel in the element IX [Eqs. (3.78)–(3.80)],

   b. CC2DCT(IX) = 0 as the second coefficient associated with the effect of the detailed geometric properties of the cross section of the main flow channel in the element IX [Eqs. (3.82)–(3.84)], and

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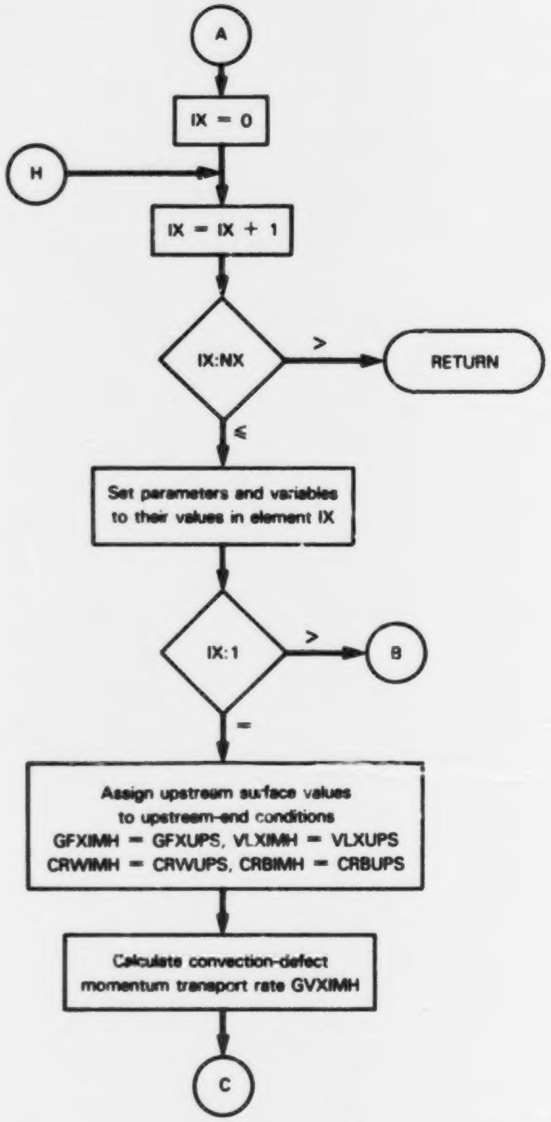
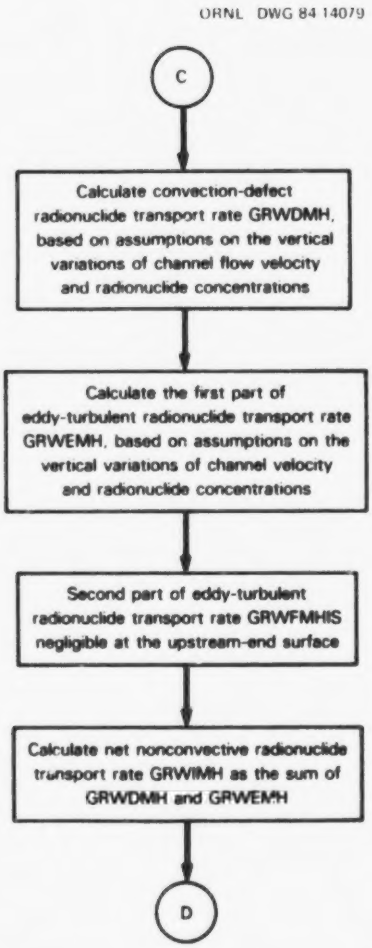

A
IX = 0
H
IX = IX + 1
IX:NX
>
RETURN
≤
Set parameters and variables to their values in element IX
IX:1
>
B
=
Assign upstream surface values to upstream-end conditions
GFXIMH = GFXUPS, VLXIMH = VLXUPS
CRWIMH = CRWUPS, CRBIMH = CRBUPS
Calculate convection-defect momentum transport rate GVXIMH
C

Fig. 6.8b. Abbreviated flowchart of the structure and computational procedure of the modular subroutine TURBUL of the RADONE computer code (continued).

c. DCTCRW(IX) = 0 as the effective value of the local, maximum vertical concentration difference of the radionuclide in the water layer $\overline{\Delta C}^*_{rw}$, representing the difference between the local water concentration of the radionuclide at the water surface and the local concentration of the radionuclide at the bottom of the water layer in the element IX [Eqs. (3.35a)–(3.56)].

The second part of the preparation stage of TURBUL reads the specified input data to the subroutine for the formulation of nonconvective transport rates (Sect. 3). The detailed definitions of this set of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C
Calculate convection-defect radionuclide transport rate GRWDMH, based on assumptions on the vertical variations of channel flow velocity and radionuclide concentrations
Calculate the first part of eddy-turbulent radionuclide transport rate GRWEMH, based on assumptions on the vertical variations of channel velocity and radionuclide concentrations
Second part of eddy-turbulent radionuclide transport rate GRWFMHIS negligible at the upstream-end surface
Calculate net nonconvective radionuclide transport rate GRWIMH as the sum of GRWDMH and GRWEMH
D

Fig. 6.8c. Abbreviated flowchart of the structure and computational procedure of the modular subroutine TURBUL of the RADONE computer code (continued).

specified input data are presented in Sects. 3 and 7; hence, the following discussions of the operational steps of the preparation stage will only state the FORTRAN variable for each coefficient or parameter and its corresponding mathematical variable and will only indicate the sections that contain its detailed definition.

3. TURBUL reads (Fig. 6.8a) and stores in the labeled COMMON/TRBCON/ the specified input data for the constant coefficients associated with the water mixture and the Blasius power-law-type model for vertical variations. This data set (Sect. 7.7) consists of

    a. NFR as n [Eqs. (3.31a) and (3.31b)],
    b. BETAFR as β [Eqs. (3.58a) and (3.58b)],
    c. VISKIN as ν [Eqs. (3.58a)–(3.59)],
    d. CCRWRB as R_{rw} [Eqs. (3.56) and (3.57a)],
    e. VFLCRW as V_{ref} [Eqs. (3.56) and (3.57b)], and
    f. PPRVFL as p_{rw} [Eqs. (3.56) and (3.57c)].

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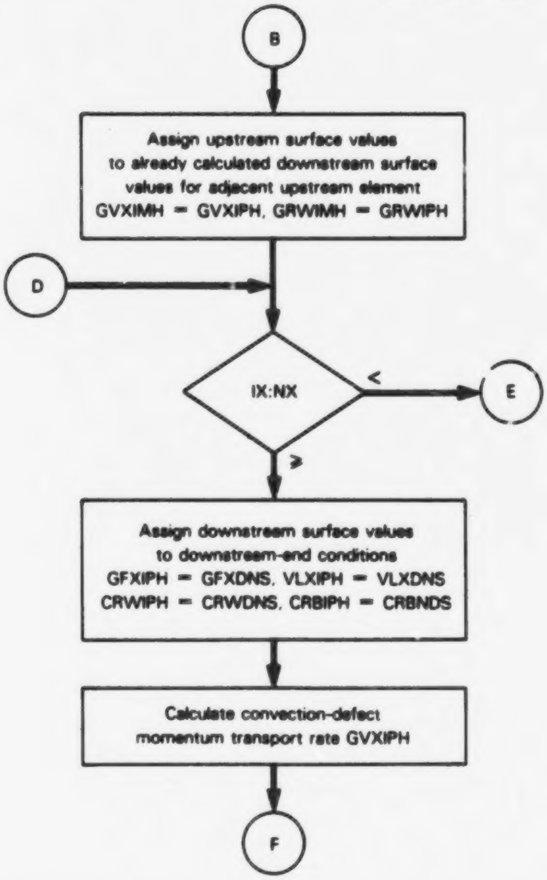
B
Assign upstream surface values to already calculated downstream surface values for adjacent upstream element GVXIMH = GVXIPH, GRWIMH = GRWIPH
D
IX:NX
<
E
≥
Assign downstream surface values to downstream-end conditions GFXIPH = GFXDNS, VLXIPH = VLXDNS CRWIPH = CRWDNS, CRBIPH = CRBNDS
Calculate convection-defect momentum transport rate GVXIPH
F

Fig. 6.8d. Abbreviated flowchart of the structure and computational procedure of the modular subroutine TURBUL of the RADONE computer code (continued).

The third part of the preparation stage of TURBUL consists of the following operational step (Fig. 6.8a):

4. For the value of the integer control parameter IWRITE = 1, which is read in the MAIN program (Sect. 6.2) and passed through the labeled COMMON/PUTOUT/, TURBUL writes as printed output (Sect. 8.8) all the specified input data required for the formulations of the nonconvective transport submodel of the RADONE computer code.

The fourth part of the preparation stage of TURBUL consists of the following operational step (Fig. 6.8a):

5. TURBUL calculates all the constant parameters used in calculations of the nonconvective transport submodel (Sect. 3), including
    a. all the constant powers, which are combinations of NFR, as the specified constant integer power of the Blasius power-law-type vertical distribution of channel flow velocity and
    b. all the constant coefficients, which are formulated in terms of

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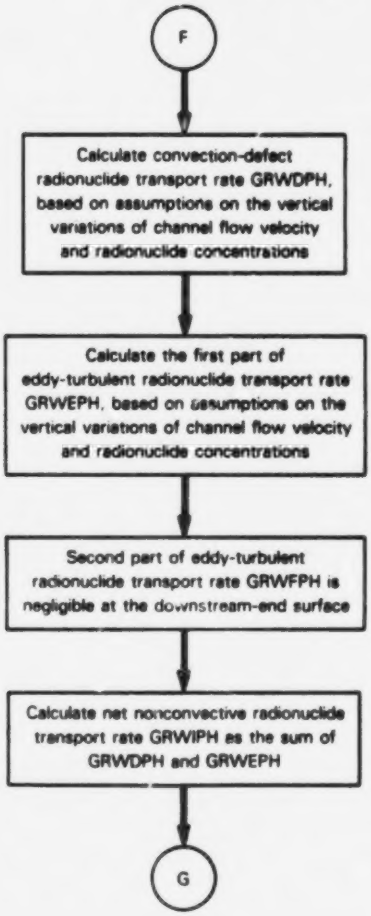

F
Calculate convection-defect radionuclide transport rate GRWDPH, based on assumptions on the vertical variations of channel flow velocity and radionuclide concentrations
Calculate the first part of eddy-turbulent radionuclide transport rate GRWEPH, based on assumptions on the vertical variations of channel flow velocity and radionuclide concentrations
Second part of eddy-turbulent radionuclide transport rate GRWFPH is negligible at the downstream-end surface
Calculate net nonconvective radionuclide transport rate GRWIPH as the sum of GRWDPH and GRWEPH
G

Fig. 6.8e. Abbreviated flowchart of the structure and computational procedure of the modular subroutine TURBUL of the RADONE computer code (continued).

(1) NFR as the specified constant integer power of the Blasius power-law-type vertical distribution of channel flow velocity,

(2) BETAFR as the specified constant bottom friction coefficient associated with the formulation of the nonconvective transport model, based on the Blasius power-law-type distribution of channel flow velocity, and

(3) VISKIN as the specified constant kinematic viscosity of mixed saline water.

At the end of the preparation stage, TURBUL completes all the necessary initialization procedures that would be required in the subsequent computation stage of the subroutine; then, it returns to the MAIN program.

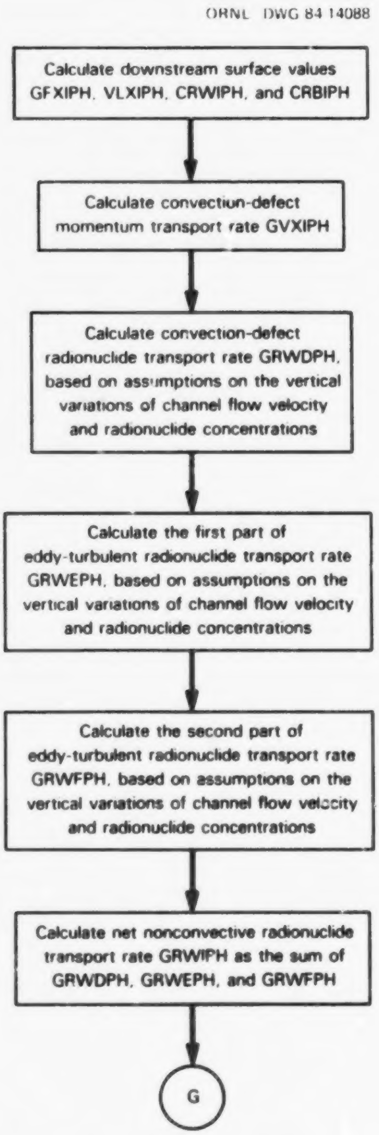
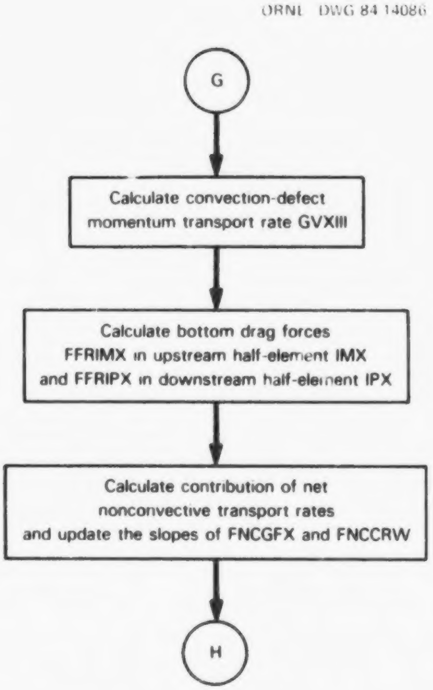

ORNL DWG 84 14088
Calculate downstream surface values GFXIPH, VLXIPH, CRWIPH, and CRBIPH
Calculate convection-defect momentum transport rate GVXIPH
Calculate convection-defect radionuclide transport rate GRWDPH, based on assumptions on the vertical variations of channel flow velocity and radionuclide concentrations
Calculate the first part of eddy-turbulent radionuclide transport rate GRWEPH, based on assumptions on the vertical variations of channel flow velocity and radionuclide concentrations
Calculate the second part of eddy-turbulent radionuclide transport rate GRWFPH, based on assumptions on the vertical variations of channel flow velocity and radionuclide concentrations
Calculate net nonconvective radionuclide transport rate GRWIPH as the sum of GRWDPH, GRWEPH, and GRWFPH
G

Fig. 6.8f. Abbreviated flowchart of the structure and computational procedure of the modular subroutine TURBUL of the RADONE computer code (continued).

6.8.2 Computation Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of the RADONE computer code, TURBUL is called by the modular subroutine SOLVER (Sect. 6.5) at every intermediate time level T of the numerical integration (solution) of the governing system of discrete-element equations of the fast-transient, one-dimensional, two-layer radionuclide transport model (Sect. 5).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G
Calculate convection-defect momentum transport rate GVXIII
Calculate bottom drag forces FFRIMX in upstream half-element IMX and FFRIPX in downstream half-element IPX
Calculate contribution of net nonconvective transport rates and update the slopes of FNCGFX and FNCCRW
H

Fig. 6.8g. Abbreviated flowchart of the structure and computational procedure of the modular subroutine TURBUL of the RADONE computer code (continued).

The first part of the computation stage of TURBUL completes the required calculations for the interpolated values of the detailed geometric properties of the main flow channel and the principal solution variables in each element and half-element, according to the following two operational steps (Fig. 6.8b):

1. Based on already calculated values, in the modular subroutine REGION, for the detailed geometric properties of the cross sections IC = 1, ..., NC, which are passed to the subroutine through the labeled COMMON/GEOEST/, the modular subroutine TURBUL calculates all the linearly interpolated values for the detailed geometric properties of the cross sections (Sect. 3.3.1) at the five locations IMH, IMX = 2*IX − 1, III = IX, IPX = 2*IX, and IPH in each element and its associated half-elements.
2. TURBUL calculates the linearly interpolated value for GFXIII as channel flow rate in the element III = IX based on already calculated values for (a) GFX(IMX) as channel flow rate in the upstream half-element IMX = 2*IX − 1 and (b) GFX(IPX) as channel flow rate in the downstream half-element IPX = 2*IX, which are passed to the subroutine through the labeled COMMON/GFXSOL/ (Appendix A).

The second part of the computation stage of TURBUL calculates nonconvective transport rates (Sect. 3) associated with the solution of the governing system of discrete-element equations for the principal solution variables (Sect. 5.2) at the upstream enclosure surface at IMH of each element IX, according to the following operational steps (Fig. 6.8b).

For IX = 1, corresponding to the upstream-end element:

3. TURBUL sets the values of the principal solution variables at the upstream enclosure surface at IMH of the upstream-end element IX = 1 equal to the already calculated, in the modular subroutine ENDCON (Sect. 6.6), upstream-end conditions for the principal solution variables, which are passed to the subroutine through the labeled COMMON/ENDFLO/ (Appendix A). These variables consist of

   a. channel flow rate at the upstream enclosure surface GFXIMH = GFLUPS as the upstream-end channel flow rate,
   b. channel flow velocity at the upstream enclosure surface VLXIMH = VLXUPS as the upstream-end channel flow velocity,
   c. water concentration of the radionuclide in the water layer at the upstream enclosure surface CRWIMH = CRWUPS as the upstream-end water concentration of the radionuclide in the water layer, and
   d. bottom concentration of the radionuclide in the bottom layer at the upstream enclosure surface CRBIMH = CRBUPS as the upstream-end bottom concentration of the radionuclide in the bottom layer.

4. Based on already calculated coefficients associated with the detailed geometric properties of the upstream-end cross section, TURBUL calculates GVXIMH as the convection-defect momentum transport rate at the upstream enclosure surface at IMH of the upstream-end element IX = 1 [Eq. (3.61a)].
5. Based on already determined values for the solution variables at the upstream-end enclosure surface at IMH, VLXIMH, CRWIMH, and CRBIMH. TURBUL calculates the maximum vertical concentration difference of the radionuclide in the water layer DCRWCR [Eq. (3.56)] at the upstream-end enclosure surface at IMH.
6. Based on already calculated coefficients associated with the detailed geometric properties of the upstream-end cross section and on the already calculated maximum vertical concentration difference of the radionuclide in the water layer DCRWCR at the upstream-end cross section, TURBUL calculates GRWDHM [Eqs. (3.56), (3.70)–(3.71b)] as the convection-defect radionuclide transport rate at the upstream enclosure surface at IMH of the upstream-end element IX = 1.
7. Based on already calculated powers and coefficients associated with NFR as the specified constant integer power of the Blasius power-law-type vertical distribution of channel flow velocity and on already calculated coefficients associated with the detailed geometric properties of the upstream-end cross section, TURBUL calculates E1FLET [Eqs. (3.76)–(3.80)] as the first, local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport at the upstream enclosure surface at IMH of the upstream-end element IX = 1.
8. Based on already calculated first, local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport E1FLET [Eqs. (3.76)–(3.80)] and the longitudinal gradient of water concentration of the radionuclide in the water layer DCRWDX [Eqs. (3.89a) and (3.90a)], TURBUL calculates GRWEMH [Eqs. (3.76), (3.87), and (3.88)] as the first part of the eddy-turbulent radionuclide transport rate at the upstream enclosure surface at IMH of the upstream-end element IX = 1.
9. TURBUL sets equal to zero, GRWFMH = 0 [Eqs. (3.76), (3.87), and (3.88)], as the second part of the eddy-turbulent radionuclide transport rate, associated with the detailed vertical concentration difference conditions of the radionuclide in the water layer, at the upstream enclosure surface at IMH of the upstream-end element IX = 1.

In general, the detailed vertical concentration difference conditions of the radionuclide in the water layer at the upstream-end enclosure surface cannot be specified accurately. Hence, it is realistic to assume that the second part of the eddy-turbulent radionuclide transport GRWFMH, associated with the detailed vertical concentration difference conditions of the radionuclide in the water layer, is negligible in comparison with the first part of the eddy-turbulent radionuclide transport rate GRWEMH at the upstream-end enclosure surface at IMH of the upstream-end element IX = 1.

10. TURBUL calculates GRWIMH as the nonconvective radionuclide transport rate (along the curvilinear longitudinal x-axis of the main flow channel) as the sum GRWIMH = GRWDMH + GRWEMH + GRWFMH [Eqs. (3.56), (3.70)–(3.71b), (3.76)–(3.80), (3.87), and (3.88)] at the upstream enclosure surface at IMH of the upstream-end element IX = 1.

For 1 < IX < NX, corresponding to the internal elements that are not at the upstream end or at the downstream end of the main flow channel:

14. TURBUL transfers directly the already calculated and stored values for the nonconvective transport rates (along the curvilinear longitudinal x-axis of the main flow channel) at the downstream enclosure surface at IPH of the upstream adjacent element IX − 1 to the values for the nonconvective transport rates at the upstream enclosure surface at IMH of the element IX. These values consist of

    a. the convection-defect momentum transport rate at the upstream enclosure surface GVXIMH = GVXIPH, which is the already calculated and stored value for the convection-defect momentum transport rate at the downstream enclosure surface IPH of the upstream adjacent element IX − 1 and

    b. the nonconvective radionuclide transport rate at the upstream enclosure surface GRWIMH = GRWIPH, which is the already calculated and stored value for the nonconvective radionuclide transport rate at the downstream enclosure surface IPH of the upstream adjacent element IX − 1.

Hence, the computational procedure of TURBUL also eliminates all duplicative calculations for the nonconvective transport rates at the common enclosure surfaces between the adjacent elements by calculating the nonconvective transport rates only at the downstream enclosure surfaces at IPH of the internal elements.

The third part of the computation stage of TURBUL calculates the nonconvective transport rates (Sect. 3) associated with the solution of the governing system of discrete-element equations for the principal solution variables (Sect. 5.2) at the downstream enclosure surface at IPH of each element IX, according to the following operational steps (Figs. 6.8d–6.8f).

For IX = NX, corresponding to the downstream-end element:

11. TURBUL sets the values of the principal solution variables at the downstream enclosure surface at IPH of the downstream-end element IX = NX equal to the already calculated, in the modular subroutine ENDCON (Sect. 6.6), downstream-end conditions for the principal solution variables, which are passed to the subroutine through the labeled COMMON/ENDFLO/ (Appendix A). These variables consist of

    a. channel flow rate at the downstream enclosure surface GFXIPH = GFLDNS as the downstream-end channel flow rate,

    b. channel flow velocity at the downstream enclosure surface VLXIPH = VLXDNS as the downstream-end channel flow velocity,

   c. water concentration of the radionuclide in the water layer at the downstream enclosure surface CRWIPH = CRWDNS as the downstream-end water concentration of the radionuclide in the water layer, and
   d. bottom concentration of the radionuclide in the bottom layer at the downstream enclosure surface CRBIPH = CRBDNS as the downstream-end bottom concentration of the radionuclide in the bottom layer.

12. Based on already calculated coefficients associated with the detailed geometric properties of the downstream-end cross section, TURBUL calculates GVXIPH as the convection-defect momentum transport rate at the downstream enclosure surface at IPH of the downstream-end element IX = NX [Eq. (3.61a)].
13. Based on already determined values for the solution variables at the downstream-end enclosure surface at IPH, VLXIPH, CRWIPH, and CRBIPH, TURBUL calculates the maximum vertical concentration difference of the radionuclide in the water layer DCRWCR [Eq. (3.56)] at the downstream-end enclosure surface at IPH.
14. Based on already calculated coefficients associated with the detailed geometric properties of the downstream-end cross section and on the already calculated maximum vertical concentration difference of the radionuclide in the water layer DCRWCR at the downstream-end cross section, TURBUL calculates GRWDPH [Eqs. (3.56), (3.70)–(3.71b)] as the convection-defect radionuclide transport rate at the downstream enclosure surface at IPH of the downstream-end element IX = NX.
15. Based on already calculated powers and coefficients associated with NFR as the specified constant integer power of the Blasius power-law-type vertical distribution of channel flow velocity and on already calculated coefficients associated with the detailed geometric properties of the downstream-end cross section, TURBUL calculates E1FLET [Eqs. (3.76)–(3.80)] as the first, local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport at the downstream enclosure surface at IPH of the downstream-end element IX = NX.
16. Based on already calculated first, local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport E1FLET [Eqs. (3.76)–(3.80)] and the longitudinal gradient of water concentration of the radionuclide in the water layer DCRWDX [Eqs. (3.89b) and (3.90a)], TURBUL calculates GRWEPH [Eqs. (3.76), (3.87), and (3.88)] as the first part of the eddy-turbulent radionuclide transport rate at the downstream enclosure surface at IPH of the downstream-end element IX = NX.
17. TURBUL sets equal to zero, GRWFPH = 0 [Eqs. (3.76), (3.87), and (3.88)], as the second part of the eddy-turbulent radionuclide transport rate associated with the detailed vertical concentration difference conditions of the radionuclide in the water layer, at the downstream enclosure surface at IPH of the downstream-end element IX = NX.

Again, in general, the detailed vertical concentration difference conditions of the radionuclide in the water layer at the downstream-end enclosure surface cannot be specified accurately. Hence, it is again realistic to assume that the second part of the eddy-turbulent radionuclide transport rate GRWFPH, associated with the detailed vertical concentration difference conditions of the radionuclide in the water layer, is negligible in comparison with the first part of the eddy-turbulent radionuclide transport rate GRWEPH at the downstream-end enclosure surface at IPH of the downstream-end element IX = NX.

18. TURBUL calculates GRWIPH as the nonconvective radionuclide transport rate (along the curvilinear longitudinal *x*-axis of the main flow channel) as the sum GRWIPH = GRDIPH + GRWEPH +

GRWFPH [Eqs. (3.56), (3.70)–(3.71b), (3.76)–(3.80), (3.87), and (3.88)] at the downstream enclosure surface at IPH of the downstream-end element IX = NX.

For 1 < IX < NX, corresponding to the internal elements that are not at the upstream end or at the downstream end of the main flow channel:

19. TURBUL determines the values of the principal solution variables in the downstream adjacent element IX + 1, and it uses these values to calculate the values of the principal solution variables at the downstream enclosure surface at IPH of the element IX. The values of the variables consist of
    a. GFXIP1 as channel flow rate in the downstream adjacent element IP1 = IX + 1,
    b. CRWIP1 as the water concentration of the radionuclide in the water layer in the downstream adjacent element IP1 = IX + 1,
    c. CRBIP1 as the bottom concentration of the radionuclide in the bottom layer in the downstream adjacent element IP1 = IX + 1,
    d. GFXIPH as channel flow rate at the downstream enclosure surface at IPH [Eq. (3.5c)],
    e. VLXIPH as channel flow velocity at the downstream enclosure surface at IPH [Eq. (3.7c)],
    f. CRWIPH as the water concentration of the radionuclide in the water layer at the downstream enclosure surface at IPH [Eq. (3.86)], and
    g. CRBIPH as the bottom concentration of the radionuclide in the bottom layer at the downstream enclosure surface at IPH [based on linear interpolation similar to [Eq. (3.86)].
20. Based on already calculated coefficients associated with the detailed geometric properties of the cross section of the downstream enclosure surface at IPH, TURBUL calculates GVXIPH as the convection-defect momentum transport rate at the downstream enclosure surface at IPH of the internal element IX [Eq. (3.61a)].
21. Based on already determined values for the solution variables at the downstream enclosure surface at IPH, VLXIPH, CRWIPH, and CRBIPH, TURBUL calculates the maximum vertical concentration difference of the radionuclide in the water layer DCRWCR [Eq. (3.56)] at the downstream enclosure surface at IPH of the internal element IX.
22. Based on already calculated coefficients associated with the detailed geometric properties of the cross section of the downstream enclosure surface at IPH and on the already calculated maximum vertical concentration difference of the radionuclide in the water layer DCRWCR at the downstream enclosure surface at IPH, TURBUL calculates GRWDPH [Eqs. (3.56), (3.70)–(3.71b)] as the convection-defect radionuclide transport rate at the downstream enclosure surface at IPH of the internal element IX.
23. Based on already calculated powers and coefficients associated with NFR as the specified constant integer power of the Blasius power-law-type vertical distribution of channel flow velocity and on already calculated coefficients associated with the detailed geometric properties of the cross section of the downstream enclosure surface at IPH, TURBUL calculates E1FLET [Eqs. (3.76)–(3.80)] as the first, local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport at the downstream enclosure surface at IPH of the internal element IX.
24. Based on already calculated first, local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport E1FLET [Eqs. (3.76)–(3.80)] and the longitudinal gradient of water concentration of the radionuclide in the water layer DCRWDX [Eqs. (3.89b) and (3.90a)], TURBUL calculates GRWEPH [Eqs. (3.76), (3.87), and (3.88)] as the first part of the eddy-turbulent radionuclide transport rate at the downstream enclosure surface at IPH of the internal element IX.

25. Based on already calculated powers and coefficients associated with NFR as the specified constant integer power of the Blasius power-law-type vertical distribution of channel flow velocity and on already calculated coefficients, associated with the detailed geometric properties of the cross section of the downstream enclosure surface at IPH, TURBUL calculates E2FLET [Eqs. (3.82)–(3.84) and (3.86)] as the local, cross-section-averaged secondary coefficient of eddy-turbulent radionuclide transport at the downstream enclosure surface IPH of the internal element IX.
26. Based on already determined values for the solution variables in the internal element IX, TURBUL calculates the maximum vertical concentration difference of the radionuclide in the water layer DCTCRW(IX) = DCRWII [Eq. (3.56)] in the internal element IX, which is stored in the labeled COMMON/TRBCON/.
27. Based on already determined values for the solution variables in the downstream adjacent element IX + 1, TURBUL calculates the maximum vertical concentration difference of the radionuclide in the water layer DCRWIP [Eq. (3.56)] in the downstream adjacent element IX + 1.
28. Based on already calculated (a) first, local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport E1FLET [Eqs. (3.76)–(3.80)] and (b) local, cross-section-averaged secondary coefficient of eddy-turbulent radionuclide transport E2FLET [Eqs. (3.82)–(3.84) and (3.86)] and the longitudinal gradients of the combinations of (c) the cross-section-averaged, detailed characteristics of the depths, $\overline{D}$, $\overline{D}_{\max}$, and $\langle D^2 \rangle$ [Eq. (3.32)], and (d) the maximum vertical concentration differences of the radionuclide in the water layer, DCRWII and DCRWIP [Eq. (3.56)], in the internal element IX and in the downstream adjacent element IX + 1, TURBUL calculates GRWFPH [Eqs. (3.76), (3.87), (3.88), (3.89b), (3.90b), and (3.90c)] as the second part of the eddy-turbulent radionuclide transport rate, associated with the detailed vertical concentration difference conditions of the radionuclide in the water layer, at the downstream enclosure surface at IPH of the internal element IX.
29. TURBUL calculates GRWIPH as the nonconvective radionuclide transport rate (along the curvilinear longitudinal *x*-axis of the main flow channel) as the sum GRWIPH = GRWDPH + GRWEPH + GRWFPH [Eqs. (3.56), (3.70)–(3.71b), (3.76)–(3.80), (3.87), and (3.88)] at the downstream enclosure surface at IPH of the internal element IX.

The fourth part of the computation stage of TURBUL calculates the bottom drag forces per unit length in the upstream half-element IMX = 2*IX − 1 and the downstream half-element IPX = 2*IX, according to the following operational step (Fig. 6.8g):

30. Based on the already calculated powers and coefficients associated with NFR as the specified constant integer power of the Blasius power-law-type vertical distribution of channel flow velocity and on the already calculated coefficients associated with the detailed geometric properties of the cross sections of the upstream half-element and the downstream half-element, TURBUL calculates the bottom drag forces per unit length in the half-elements. These forces consist of

    a. FFRIMX as the bottom drag force per unit length in the upstream half-element IMX = 2*X − 1 [Eq. (3.58a)] and
    b. FFRIPX as the bottom drag force per unit length in the downstream half-element IPX = 2*IX [Eq. (3.58a)].

The fifth part of the computation stage of TURBUL calculates the convection-defect momentum transport rate in each element IX, which corresponds to the common enclosure surface between the

2+[

upstream half-element IMX = 2*IX − 1 and the downstream half-element IPX = 2*IX, according to the following operational step (Fig. 6.8g).

31. Based on the already calculated coefficients associated with NFR as the specified constant integer power of the Blasius power-law-type vertical distribution of channel flow velocity and on the already calculated coefficients associated with the detailed geometric properties of the cross section of the element IX, TURBUL calculates GVXIII as the convection-defect momentum transport rate at the enclosure surface at III = IX in the element IX [Eq. (3.61a)].

The sixth part of the computation stage of TURBUL completes the second step of the successive updating scheme [Eqs. (5.24a)–(5.24c)] used in the numerical integration (solution) of the governing system of discrete-element equations of the mathematical model (Sect 5.2) of the RADONE computer code by calculating the terms representing the contribution of nonconvective transport (convection-defect transport and eddy-turbulent transport, along the curvilinear longitudinal *x*-axis of the main flow channel) to the right-hand-side solution functions for the solution of the principal solution variables in each element and half-element, according to the following three operational steps (Fig. 6.8g).

32. TURBUL calculates, at each intermediate time level T, the part representing the nonconvective momentum transport [Eq. (5.24a)] as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IMX), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IMX) in the upstream half-element IMX = 2*IX − 1 [Eq. (5.2a)].
33. TURBUL calculates, at each intermediate time level T, the part representing nonconvective momentum transport [Eq. (5.24b)] as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IPX), which is stored in the labeled COMMON/GFXSOL/, for the solution of the channel flow rate GFX(IPX) in the downstream half-element IPX = 2*IX [Eq. (5.3a)].
34. TURBUL calculates, at each intermediate time level T, the part representing nonconvective radionuclide transport (convection-defect radionuclide transport and eddy-turbulent radionuclide transport, along the curvilinear longitudinal *x*-axis of the main flow channel) [Eq. (5.24c)] as the additional term to the value of the right-hand-side solution function (slope) FNCCRW(IX), which is stored in the labeled COMMON/CRWSOL/, for the solution of water concentration of the radionuclide in the water layer CRW(IX) in the element IX [Eq. (5.4a)].

At the end of the computation stage, TURBUL completes the calculations, at the intermediate time level T, for all the terms associated with nonconvective transport (convection-defect transport and eddy-turbulent transport, along the curvilinear longitudinal *x*-axis of the main flow channel), which represent the second step in the computational construction of the right-hand-side solution functions for the solutions of the principal solution variables in all elements and half-elements, according to the successive updating scheme, used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide model (Sect. 5.2) of the RADONE computer code; then, it returns to the modular subroutine SOLVER.

6.9 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE GROUND

The modular subroutine GROUND represents the computational algorithm for formulating the contribution of the transport associated with groundwater seepage flow into or out of the main flow channel to the solution of flow and radionuclide concentration conditions in the NX number of elements and 2*NX number of half-elements, according to the one-dimensional formulation of the discrete-element model of the RADONE computer code (Sects. 2, 3.6, 4.6, and 5.2). GROUND is the third of the eight major modular subroutines that are called by the computational procedure of the modular subroutine SOLVER, according to the sequential computational method [Eqs. (5.25a)–(5.25e)], based on the successive updating scheme for the solution of the 5*NX number of right-hand-side solution functions, consisting of (1) $[\overline{F}_{GRD}(\overline{H})]_i$ in all N elements [Eqs. (5.7) and (5.25a)], (2) $[\overline{F}_{GRD}(\overline{G}_x)]_{i-1/4}$ in all N upstream half-elements [Eqs. (5.13) and (5.25b)], (3) $[F_{GRD}(\overline{G}_x)]_{i+1/4}$ in all N downstream half-elements [Eqs. (5.19) and (5.25c)], (4) $[F_{GRD}(\overline{C}_{rw})]_i$ in all N elements [Eqs. (2.7) and (5.25d)], and (e) $[F_{GRD}(\overline{C}_{rb})]_i$ in all N elements [Eqs. (2.17) and (5.25e)].

The definitions of the parameters and coefficients, associated with the formulation the groundwater seepage flow conditions (Sects. 3.6 and 4.6), which are included in the sets of specified input data to the RADONE computer code, will not be repeated in this section for the presentation of the structure and computational procedure of the modular subroutine GROUND because the detailed definitions of all required parameters and coefficients are included in Sect. 7.9, which presents the discussions of the specified input data for the modular subroutine GROUND. Furthermore, since an extensive and detailed presentation of the general structure and computational procedure of GROUND for all the fast-transient, one-dimensional transport models of the UTA project [Eraslan et al. (1976), Eraslan and Witten (1984)] is presented in the users manual of the ESTONE computer code [Eraslan (1983)] of the thermal program of UTA, this section will only present the structure and computational procedure of the modular subroutine GROUND in a summary form, which would include all the necessary information that would be required by the user in implementing the RADONE computer code.

The structure and computational procedure of GROUND (Figs. 6.9a and 6.9b) consist of two operational stages, the preparation stage and the computation stage, which are initiated and completed, depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.9.1 Preparation Stage

GROUND is first called from the MAIN program, with the value of the integer control parameter KRUN = 0 (Fig. 6.2), which is passed to the subroutine through the labeled COMMON/CONTRL/.

GROUND first reads (Fig. 6.9a) the specified input data (Sect. 7.9) for

1. ICNGRD as the integer control parameter that represents the user-specified option for excluding or including the contribution of the transport associated with groundwater seepage flow into or out of the main flow channel to the solution of principal flow variables in the main flow channel (Sect. 6.5) and
2. NGRPER as the specified number of time periods for formulating the temporal variations of groundwater seepage flow conditions in the geographic (climatological) region of the main flow channel.

The specified value of the integer control parameter ICNGRD is stored in the labeled COMMON/CALLER/, and it is passed to the modular subroutine SOLVER (Sect. 6.5).

For the value of the integer control parameter ICNGRD = 0, which represents the user-specified option for excluding the contribution of the transport associated with groundwater seepage flow into or out of the main flow channel to the solution of the principal solution variables in the main flow channel (Sect. 6.5),

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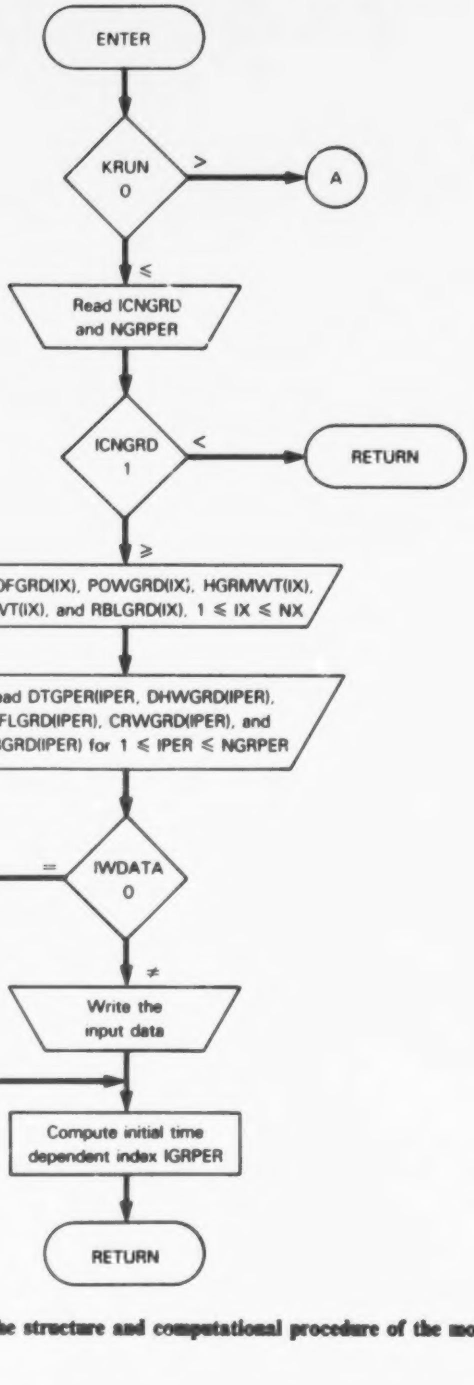
ENTER
KRUN
0
>
A
≤
Read ICNGRD and NGRPER
ICNGRD
1
<
RETURN
≥
Read COFGRD(IX), POWGRD(IX), HGRMWT(IX), GRFMWT(IX), and RBLGRD(IX), 1 ≤ IX ≤ NX
Read DTGPER(IPER, DHWGRD(IPER), CFLGRD(IPER), CRWGRD(IPER), and CRBGRD(IPER) for 1 ≤ IPER ≤ NGRPER
IWDATA
0
=
≠
Write the input data
Compute initial time dependent index IGRPER
RETURN

Fig. 6.9a. Abbreviated flowchart of the structure and computational procedure of the modular subroutine GROUND of the RADONE computer code.

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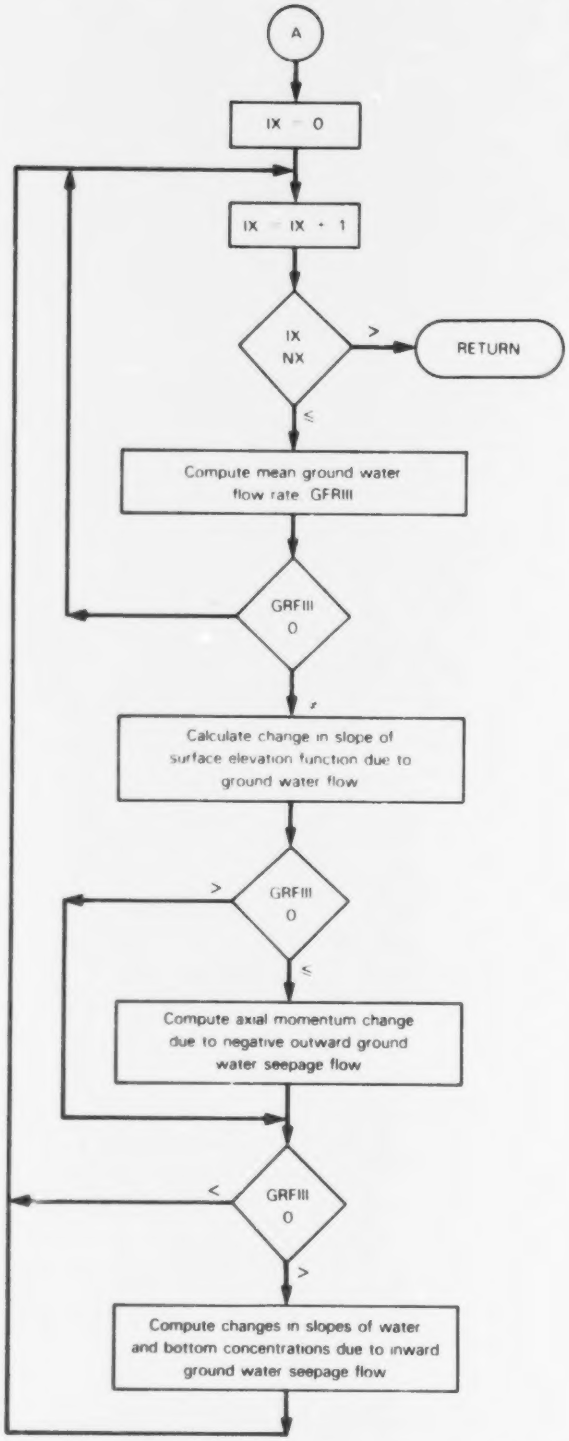
A
IX = 0
IX = IX + 1
IX
NX
>
RETURN
≤
Compute mean ground water flow rate GFRIII
GRFIII
0
≠
Calculate change in slope of surface elevation function due to ground water flow
>
GRFIII
0
≤
Compute axial momentum change due to negative outward ground water seepage flow
<
GRFIII
0
>
Compute changes in slopes of water and bottom concentrations due to inward ground water seepage flow

Fig. 6,9b. Abbreviated flowchart of the structure and computational procedure of the modular subroutine GROUND of the RADONE computer code (continued).

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GROUND returns to the MAIN program, without any additional operational steps because it does not need to read any additional specified input data.

For the value of the integer control parameter ICNGRD = 1 (or > 0), which represents the user-specified option for including the contribution of the transport associated with groundwater seepage flow into or out of the main flow channel to the solution of the principal flow variables in the main flow channel (Sect. 6.5), GROUND initiates the first part of the preparation stage for reading the specified input data for the geophysical conditions of the bed of the main flow channel in the geographic (climatological) region of the river or estuary, which control groundwater seepage flow into or out of the elements IX = 1, ..., NX of the main flow channel (Sect. 4.6), according to the following operational step (Fig. 6.9a):

1. GROUND reads (Fig. 6.9a) and stores in labeled COMMON/GRDCON/ (Appendix A) the set of specified input (Sect. 7.9) data for the temporally uniform geophysical conditions associated with the groundwater seepage flow into or out of the main flow channel in all elements IX = 1, ..., NX (Sects. 3.6 and 4.6). This data set consists of

    a. COFGRD(IX) as $R_{grd,por;i}$ [Eqs. (3.84) and (4.55)],
    b. POWGRD(IX) as $r_{grd;i}$ [Eqs. (3.85) and (4.57)],
    c. HGRMWT(IX) as $H_{grd,mwt;i}$ [Eqs. (3.85) and (4.56)],
    d. GRFMWT(IX) as $G_{grd,avg;i}$ [Eqs. (3.84) and (4.58)], and
    e. RBLGRD(IX) as $R_{bl,grd;i}$ [Eqs. (3.89) and (4.59)].

The second part of the preparation stage of GROUND reads the specified input data for the spatially averaged conditions that approximately represent the temporal variations of groundwater seepage flow conditions into or out of the main flow channel in the geographic (climatological) region of the river or estuary, according to the following operational step (Fig. 6.9a):

2. GROUND reads the specified set of input data as IPER = 1, ..., NGRPER lists of records (Sect. 7.9) for the durations of the specified time periods (Sect. 4.6) and the detailed information about groundwater seepage flow conditions into or out of the main flow channel, during the specified time periods. This data set consists of

    a. DTGPER(IPER) as $\Delta t_{grd,p}$ [Eqs. (4.60), (4.61), (4.63), and (4.64)],
    b. DHWGRD(IPER) as $\Delta H_{grd,reg,p}$ [Eq. (4.61)],
    c. CFLGRD(IPER) as $R_{grd,reg,p}$ [Eq. (4.60)],
    d. CRWGRD(IPER) as $C_{rw,grd,wl,p}$ [Eq. (4.63)], and
    e. CRBGRD(IPER) as $C_{rb,grd,bl,p}$ [Eq. (4.64)].

It is important to point out that extensive specified input data sets for groundwater seepage flow conditions are required only for long-term and accurate representations of the temporal variations of the principal solution variables associated with groundwater seepage flow into or out of the main flow channel for obtaining long-term and accurate computer simulations, by the application of the RADONE computer code, for flow conditions and radionuclide concentration conditions in a controlled river or a tidal estuary. In most applications of the RADONE computer code to the simulations of flow and radionuclide concentration conditions in a large river or an estuary, the effect of groundwater seepage flow can be neglected by simply specifying the value of the integer control parameter ICNGRD = 0 in the first data record for the subroutine GROUND. For temporally uniform conditions for groundwater seepage flow into or out of the main flow channel, only a single-record specified input data set, with IPER = NGRPER = 1, would be sufficient to represent the temporally uniform conditions for the principal solution variables of groundwater seepage flow into or out of the main flow channel. Hence, although GROUND includes all the necessary capabilities for incorporating detailed information about groundwater seepage flow conditions into or out of the main flow channel, based on extensive specified input data sets, it also includes provisions to allow the user to implement the RADONE computer code based on simplified groundwater seepage flow conditions into or out of the main flow channel, which require only simple specified input data sets with a very limited number of data records.

The third part of the preparation stage of GROUND consists of the following operational step (Fig. 6.11a):

3. For the value of the integer control parameter IWDATA = 1, which is read in the MAIN program (Sect. 6.2) and passed through the labeled COMMON/PUTOUT/, GROUND writes as printed output (Sect. 8.9) all the specified input data for groundwater seepage flow conditions into or out of the main flow channel in the geographic (climatological) region of the river or estuary.

The fourth part of the preparation stage of GROUND also includes the special feature that enables the user to implement the RADONE computer code with minimal amount of effort in simulating accurately the detailed flow conditions and radionuclide concentration conditions in an actual controlled river or a tidal estuary, based on extensive specified input data for groundwater seepage flow conditions into or out of the main flow channel. The structure and computational procedure of GROUND include special provisions for aligning the time periods of the specified input data for groundwater seepage flow conditions into or out of the main flow channel with the internally calculated time levels of the solution, according to the general computational algorithm of the RADONE computer code. Hence, if the user already has extensive sets of specified input data for groundwater seepage flow conditions into or out of the main flow channel and for radionuclide concentration conditions for a long overall period (e.g., one week, one month, and one year) with a large number of specified time periods (Sect. 4.6) for representing short-term variations (e.g., 1 h, 1 d, or 1 week), the computer simulations with the RADONE computer code can be started at any time within the overall period of the available data, without requiring any modifications of the extensive sets of input data. The internal computational algorithm of the preparation stage of GROUND automatically aligns the specified initial time (Sect. 6.4) with the appropriate specified time period of the specified input data for groundwater seepage flow conditions in the geographic (climatological) region of the main flow channel. The fourth part of GROUND initiates and completes the necessary procedure for determining the appropriate specified time period and the specified input data for groundwater seepage flow conditions that correspond to the specified initial time (Sect. 6.4), according to the following operational step (Fig. 6.9a):

4. For the specified initial time T, which is read in the modular subroutine INITAL (Sect. 6.4) and passed through the labeled COMMON/CONTRL/, GROUND determines the appropriate specified time period for the specified input data for groundwater seepage flow conditions into or out of the main flow channel DTGPER(IPER), which include the specified initial time T, as IGRPER = IPE (Fig. 6.9a).

At the end of the preparation stage, GROUND completes all the necessary initialization procedures that would be required in the subsequent computation stage of the subroutine; then, it returns to the MAIN program.

6.9.2 Computation Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of RADONE, GROUND is called by the modular subroutine SOLVER at every intermediate time level of the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5).

The first part of the computation stage of GROUND determines the appropriate time period for the specified input data for groundwater seepage flow conditions in the geographic (climatological) region of the main flow channel that correspond to the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, according to the following operational step (Fig. 6.9b):

1. Based on the value of the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, GROUND determines the appropriate specified time period for the specified input data for groundwater seepage flow conditions in the geographic (climatological) region of the main flow channel DTGPER(IPER). If the intermediate time level T extends beyond the specified time corresponding to the end of the last input record for the specified time period DTGPER(NGRPER), GROUND automatically retains the last specified time period DTGPER(NGRPER); and it determines groundwater seepage flow conditions in the geographic (climatological) region of the main flow channel, based on the specified input data for the last specified period DTGPER(NGRPER).

The second part of the computation stage of GROUND completes the third step of the successive updating scheme [Eqs. (5.25a)–(5.25e)] used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code by calculating the terms representing the contribution of transport associated with groundwater seepage flow into or out of the main flow channel to the right-hand-side solution functions for the solution of the principal solution variables in each element and half-element, according to the following operational steps (Fig. 6.9b):

2. Based on values already calculated, in the modular subroutine REGION, for the detailed geometric properties of the cross sections IC = 1, ..., NC, which are passed to the subroutine through the labeled COMMON/GEOEST/, GROUND calculates all the required linearly interpolated values for the detailed geometric properties of the cross sections (Sect. 3.3.1) at three locations in each element. These locations are (a) in the upstream half-element IMX = 2*IX − 1, (b) in the element III = IX, and (c) in the downstream half-element IPX = 2*IX.
3. GROUND calculates all the required values of the principal solution variables in each element and half-element. These values consist of
    a. HSRIII = HSR(IX) as water surface elevation, which is passed to the subroutine through the labeled COMMON/HSRSOL/, in the element IX,
    b. GFXIMX = GFX(IMX) as channel flow rate (along the curvilinear longitudinal *x*-axis of the main flow channel), which is passed to the subroutine through the labeled COMMON/GFXSOL/, in the upstream half-element IMX = 2*IX − 1,
    c. GFXIPX = GFX(IPX) as channel flow rate, which is passed to the subroutine through the labeled COMMON/GFXSOL/, in the downstream half-element IPX = 2*IX,
    d. VLXIMX as channel flow velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) in the upstream half-element IMX = 2*IX − 1, and
    e. VLXIPX as channel flow velocity in the downstream half-element IPX = 2*IX.

4. GROUND calculates HWTGRD as water surface elevation in the groundwater table in the geographic (climatological) region of the main flow channel, at the intermediate time level T, associated with the element IX [Eqs. (3.85) and (4.61)].
5. GROUND calculates GRFGGR as the regional groundwater seepage flow rate into or out of the main flow channel, at the intermediate time level T, into or out of the element IX [Eqs. (3.84) and (4.60)].
6. GROUND calculates GGRDHW as the hydrostatic groundwater seepage flow flux, at the intermediate time level T, into or out of the element IX [Eqs. (3.85), (3.86), and (4.61)].
7. GROUND calculates GRFIII as the net groundwater seepage flow rate, at the intermediate time level T, into or out of the element IX [Eq. (3.87)].
8. GROUND calculates GRFRBL as the groundwater seepage flow rate into or out of the bottom layer in the element IX, at the intermediate time level T [Eq. (3.89)].
9. GROUND calculates, at each intermediate time level T, the part representing the water mass transport associated with groundwater seepage flow into or out of the main flow channel [Eq. (5.7)] as the additional term to the value of the right-hand-side solution function (slope) FNCHSR(IX), which is stored in the labeled COMMON/HSRSOL/, for the solution of water surface elevation HSR(IX) in the element IX [Eq. (5.25a)].
10. The formulation of groundwater seepage flow conditions assumes that the velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of groundwater seepage flow into the main flow channel is negligible [Eq. (3.21a)]. Hence, according to the generalized, nonspatial, upwind-differencing interpolation form for specified-flow transport [Eq. (3.21a)], GROUND completely omits the calculations of the parts representing the momentum transport associated with groundwater seepage flow into the main flow channel, GRFII > 0 [Eqs. (5.13) and (5.19)] and, hence, omits the additional term to the right-hand-side solution functions (slopes) FNCGFX(IMX) and FNCGFX(IPX) [Eqs. (5.25b) and (5.25c)].
11. For the net groundwater seepage flow rate out of the main flow channel, GRFIII < 0 [Eq. (3.21b)], GROUND calculates, at each intermediate time level T, the part representing the momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with groundwater seepage flow out of the main flow channel [Eq. (5.13)] as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IMX), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IMX) in the upstream half-element IMX = 2*IX − 1 [Eq. (5.25b)].
12. For the net groundwater seepage flow rate out of the main flow channel, GRFIII < 0 [Eq. (3.21b)], GROUND calculates, at each intermediate time level T, the part representing the momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with groundwater seepage flow out of the main flow channel [Eq. (5.19)] as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IPX), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IPX) in the downstream half-element IPX = 2*IX [Eq. (5.25c)].
13. For the net groundwater seepage flow rate out of the main flow channel, GRFIII < 0, GROUND completely omits the calculations of the parts representing
    a. the radionuclide transport effect associated with the groundwater seepage flow out of the water layer of the main flow channel in element IX [Eqs. (2.7) and (5.25d)] and
    b. the radionuclide transport effect associated with the groundwater seepage flow out of the bottom layer of the main flow channel in element IX [Eqs. (2.17) and (5.25e)],

according to

a. the "intensive" form of the discrete-element formulations of the parts representing the radionuclide transport in (1) the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)] and (2) the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)] and

b. the generalized, nonspatial, upwind-differencing interpolation forms for the specified-transport for (1) water concentration of the radionuclide in the water layer [Eqs. (3.22a) and (3.22b)] and (2) bottom concentration of the radionuclide in the bottom layer [Eqs. (3.23a) and (3.23b)],

associated with groundwater seepage flow out of the main flow channel, GRFIII < 0.

14. For groundwater seepage flow rate into the main flow channel GRFIII > 0 [Eq. (3.22a)], GROUND calculates, at each intermediate time level T, the part representing the radionuclide transport associated with the groundwater seepage flow into the water layer in the main flow channel [Eq. (5.25d)] as the additional term to the value of the right-hand-side solution function (slope) FNCCRW(IX), which is stored in the labeled COMMON/CRWSOL/, for the solution of water concentration of the radionuclide in the water layer CRW(IX) in the element IX [Eq. (5.4a)].
15. For groundwater seepage flow rate into the main flow channel GRFIII > 0 [Eq. (3.23a)], GROUND calculates, at each intermediate time level T, the part representing the radionuclide transport associated with the groundwater seepage flow into the bottom layer in the main flow channel [Eq. (5.25e)] as the additional term to the value of the right-hand-side solution function (slope) FNCCRB(IX), which is stored in the labeled COMMON/CRBSOL/, for the solution of bottom concentration of the radionuclide in the bottom layer CRB(IX) in the element IX [Eq. (5.5a)].

At the end of the computation stage, GROUND completes all the calculations at the intermediate time level T, for all terms representing the transport associated with groundwater seepage flow into or out of the main flow channel, which collectively represent the third step in the computational construction of all the right-hand-side solution functions for the solutions of the principal solution variables in all elements and half-elements, according to the successive updating scheme, used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code; then, it returns to the modular subroutine SOLVER.

The structure and computational procedure of GROUND of the advanced development program version of the RADONE computer code were specifically designed to enable the user to understand, without undue difficulty, (1) the requirements for the preparation of the specified input data and (2) the computational algorithms associated with formulations of the temporally and spatially varying conditions of groundwater seepage flow into or out of the main flow channel which are generally encountered in applications of the computer code for the assessment of the radiological impact on the receiving water body that would result from accidental radiological release scenarios that can contaminate the groundwater in the geographic (climatological) region of a river or an estuary. Hence, the structure of GROUND reads and stores all the specified sets of input data for groundwater seepage flow conditions in the geographic (climatological) region of the main flow channel for all the specified time periods in the structurally separated part associated with the preparation stage of the subroutine. In certain applications of the RADONE computer code for continuous, long-term, and accurate simulations of flow and radionuclide concentration conditions in a controlled river or a tidal estuary during a relatively long period (e.g., six months), based on specified sets of input data with relatively high temporal resolution (e.g., 1 d or 1 h), GROUND could also require

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substantial storage. Particularly in computer systems operating in an interactive, time-sharing mode, this excessive storage requirement of GROUND could become a problem because excessive core storage allocations to the program could also reduce the overall computational speed of the complete system. This problem can (and should) be avoided by considering successive runs with the RADONE computer code for shorter simulation periods (e.g., one month) and only with the parts of the specified input data sets required for each particular simulation period. Because the RADONE computer code automatically includes the necessary restart capability through the modular subroutine OUTPUT (Sect. 6.5) and the modular subroutine INITAL (Sects. 6.4 and 7.4), the user can (and should) separate the specified sets of the input data for a relatively long simulation period (e.g., six months) into partial specified sets of input data for relatively shorter simulation periods (e.g., one month) and apply the code successively by restarting the computations for each successive, relatively shorter period.

The production program version of the RADONE computer code can completely eliminate the storage requirement for the specified sets of input data for each specified time period for groundwater seepage flow conditions in the geographic (climatological) region of the main flow channel of a river or an estuary by combining the preparation stage and the computation stage into a single computation stage in the modular subroutine GROUND.

6.10 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE BOTTOM

The modular subroutine **BOTTOM** represents the computational algorithm for formulating the contribution of the net bottom radionuclide transport effect (Sect. 3.5), between the water layer and the bottom layer, which consists of the combination of (1) the bottom-mixing radionuclide transport effect (Sect. 5.3.1), (2) the bottom-settling radionuclide transport effect (Sect. 5.3.2), and (3) the bottom-resuspension radionuclide transport effect (Sect. 5.3.3), to the solution of radionuclide concentration conditions in the NX number of elements, according to the one-dimensional formulation of the discrete-element model of the RADONE computer code (Sects. 2, 3.5, and 5.2). BOTTOM is the fourth of the eight major modular subroutines that are called by the computational procedure of the modular subroutine SOLVER, according to the sequential computational method [Eqs. (5.26a) and (5.26b)], based on the successive updating scheme for the solution of 2*NX number of right-hand-side solution functions, consisting of (a) $[F_{BOT}(\overline{C}_{rw})]_i$ in all N elements [Eqs. (2.8) and (5.26a)] and (b) $[F_{BOT}(\overline{C}_{rb})]_i$ in all N elements [Eqs. (2.18) and (5.26b)].

The structure and computational procedure of BOTTOM (Figs. 6.10a and 6.10b) consist of two operational stages, preparation stage and computation stage, which are initiated and completed, depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.10.1 Preparation Stage

The modular subroutine BOTTOM is first called from the MAIN program with the value of the integer control parameter KRUN = 0 (Fig. 6.2), which is passed to the subroutine through the labeled COMMON/CONTRL/.

BOTTOM initiates and completes the first part of the preparation stage according to the following operational step (Fig. 6.10a):

1. BOTTOM first reads (Fig. 6.10a) the specified input data (Sect. 7.10) for ICNBOT as the user-specified integer control parameter for excluding or including the contribution of the bottom

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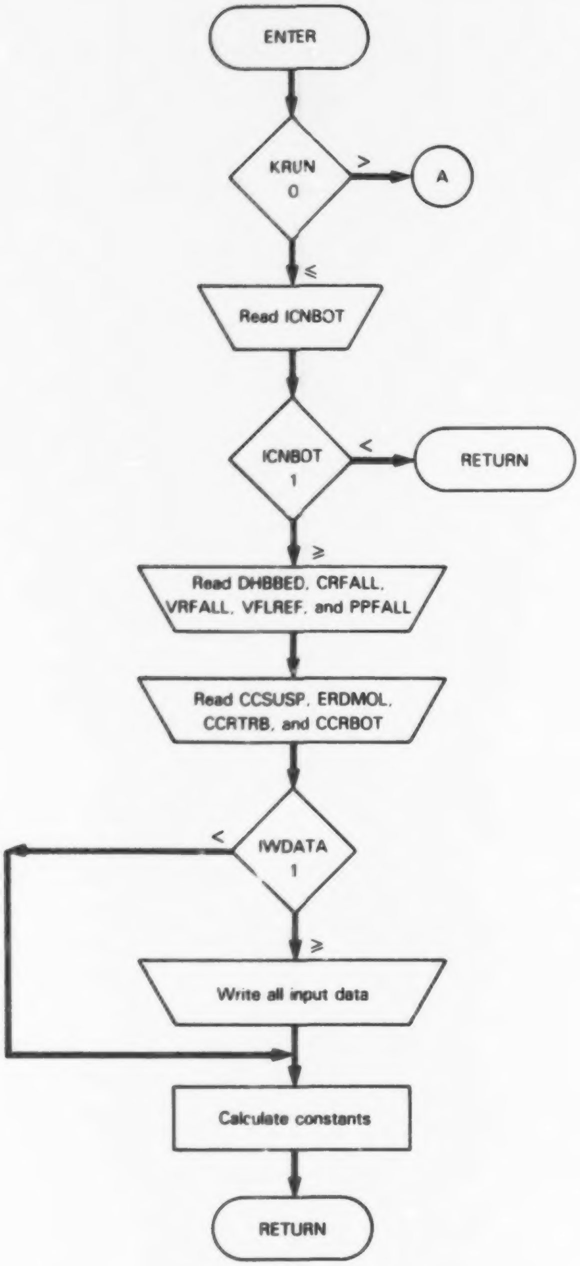
ENTER
KRUN
0
>
A
≤
Read ICNBOT
ICNBOT
1
<
RETURN
≥
Read DHBBED, CRFALL,
VRFALL, VFLREF, and PPFALL
Read CCSUSP, ERDMOL,
CCRTRB, and CCRBOT
IWDATA
1
<
≥
Write all input data
Calculate constants
RETURN

Fig. 6.10a. Abbreviated flowchart of the structure and computational procedure of the modular subroutine BOTTOM of the RADONE computer code.

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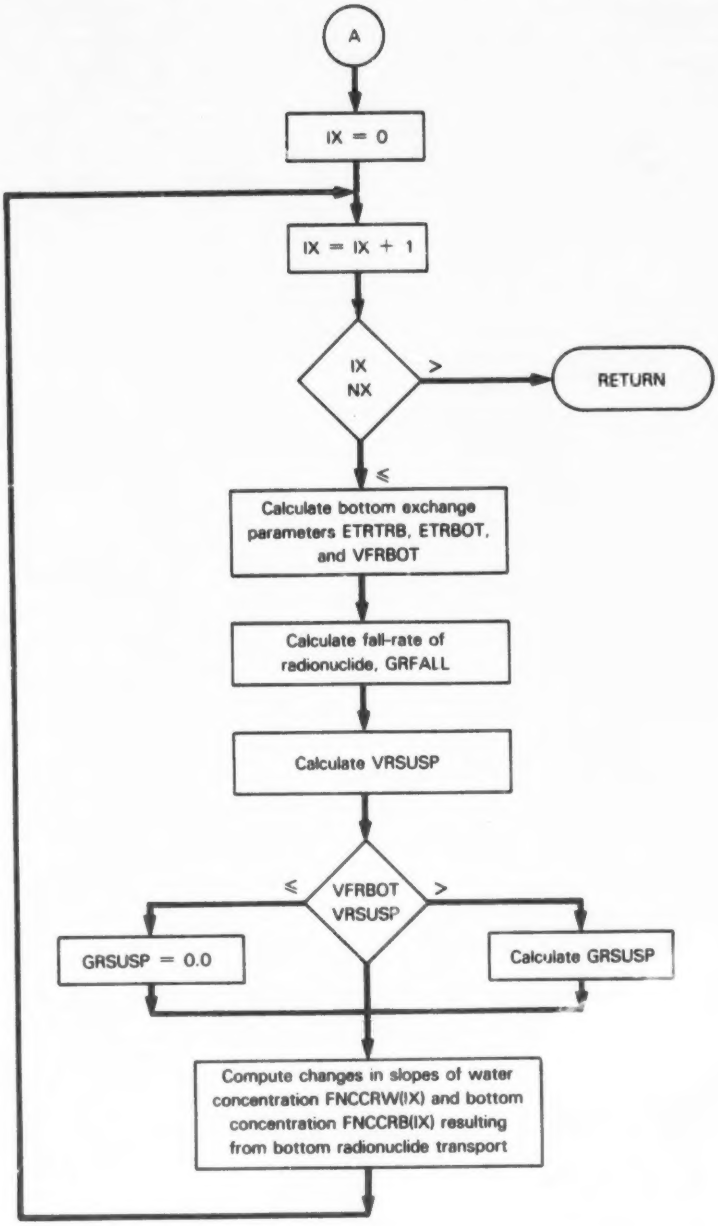
A
IX = 0
IX = IX + 1
IX
NX
>
RETURN
≤
Calculate bottom exchange parameters ETRTRB, ETRBOT, and VFRBOT
Calculate fall-rate of radionuclide, GRFALL
Calculate VRSUSP
≤
VFRBOT
VRSUSP
>
GRSUSP = 0.0
Calculate GRSUSP
Compute changes in slopes of water concentration FNCCRW(IX) and bottom concentration FNCCRB(IX) resulting from bottom radionuclide transport

Fig. 6.10b. Abbreviated flowchart of the structure and computational procedure of the modular subroutine BOTTOM of the RADONE computer code (continued).

radionuclide transport effects between the water layer and the bottom layer, to the solution of the radionuclide concentration conditions in the main flow channel (Sect. 6.5).

For the specified input data for ICNBOT = 0, which correspond to the user-specified option for excluding the contribution of the bottom radionuclide transport effects, between the water layer and the bottom layer, to the solution of the radionuclide concentration conditions in the main flow channel, BOTTOM returns to the MAIN program without any further procedural step (Fig. 6.10a) because it does not need to read any additional specified input data.

For the specified input data for ICNBOT = 1 (greater than zero), which corresponds to the user-specified option for including the contribution of the bottom radionuclide transport effects, between the water layer and the bottom layer, to the solution of the radionuclide concentration conditions in the main flow channel (Sect. 6.5), BOTTOM proceeds with the part of the preparation stage for reading the specified input data (Sect. 7.10) for the calculation of the bottom radionuclide transport rates in the elements of the computational flow region. The detailed definitions of this set of specified input data are presented in Sects. 3.5 and 7.10. Hence, the following discussion of the operational steps of the preparation stage will only state the FORTRAN variable for each parameter or coefficient and its corresponding mathematical variable; and it will also indicate the sections that contain its definition.

2. BOTTOM first reads (Fig. 6.10a) and stores in the labeled COMMON/BEDCON/ (Appendix A) the specified input data (Sect. 7.10) for the following parameters and coefficients:

   a. DHBBED as D_{bl} [Eqs. (2.16)–(2.20)],
   b. CRFALL as $R_{rw,fall}$ [Eqs. (3.74) and (3.75a)],
   c. VRFALL as $V_{rw,fall}$ [Eqs. (3.74) and (3.75b)],
   d. VFLREF as $V_{ref,fall}$ [Eqs. (3.74) and (3.75c)], and
   e. PPFALL as p_{fall} [Eqs. (3.74) and (3.75d)].

3. BOTTOM next reads (Fig. 6.10a) and stores in the labeled COMMON/BEDCON/ (Appendix A) the specified input data (Sect. 7.10) for the following additional parameters and coefficients:

   a. CCSUPS as $R_{rb,susp}$ [Eq. (3.79)],
   b. ERDMOL as $\epsilon_{bot,\min}$ [Eqs. (3.72) and (3.73c)],
   c. CCRTRB as $k_{rw,bot}$ [Eqs. (3.72) and (3.73b)], and
   d. CCRBOT as $R_{bot,trb}$ [Eqs. (3.72) and (3.73a)].

The second part of the preparation stage of BOTTOM consists of the following operational step (Fig. 6.10a):

4. For the specified value of the integer control parameter IWRITE = 1, which is read in the MAIN program (Sect. 6.2) and passed through the labeled COMMON/PUTOUT/, BOTTOM writes as printed output (Sect. 8.10) all the specified input data for the parameters and coefficients required for the formulation of the bottom radionuclide transport rates, between the water layer and the bottom layer in the main flow channel of a river or an estuary.

The third part of the preparation stage of BOTTOM utilizes the coefficients and parameters, associated with the nonconvective transport submodel (Sect. 3.4), which were read in the modular subroutine TURBUL (Sects. 6.8 and 7.8) and passed through the labeled COMMON/TRBCON/, according to the following computational step:

5. For the specified values of coefficients NFR and BETA, which were read in the modular subroutine TURBUL and passed through the labeled COMMON/TRBCON/, BOTTOM calculates all the required constant coefficients and parameters used in the formulation of the bottom radionuclide transport rates, between the water layer and the bottom layer, including

    a. all the constant powers, which are combinations of NFR, consisting of PN, PNP1, PNM1, P111, P222, P1N1, P1NN, and P2NN (Sects. 3.4 and 7.8),
    b. ETRVIS as the constant coefficient associated with the local, isotropic, depth-averaged coefficient of eddy-turbulent radionuclide transport [Eqs. (3.54), (3.58)–(3.60), and (3.72)], and
    c. CNFBFR as the constant coefficient associated with the local bottom shear velocity based on the bottom shear stress [Eqs. (3.77a) and (3.77b)].

At the end of the preparation stage, BOTTOM completes all the necessary initialization procedures that would be required for the subsequent computation stage of the subroutine; then, it returns to the MAIN program.

6.10.2 Computation Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of RADONE, BOTTOM is called by the modular subroutine SOLVER at every intermediate time level T of the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5).

The computation stage of BOTTOM completes the fourth step of the successive updating scheme [Eqs. (5.26a) and (5.26b)] used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code by calculating the terms representing the contribution of the net bottom radionuclide transport effects, between the water layer and the bottom layer (Sect. 3.5), consisting of the bottom-mixing radionuclide transport effects (Sect. 3.5.1), bottom-settling radionuclide transport effects (Sect. 3.5.2), and bottom-resuspension radionuclide transport effects (Sect. 3.5.3) at the common bottom enclosure surfaces that separate the water layer from the bottom layer, in all the elements of the main flow channel.

The first part of the computation stage of BOTTOM completes the following operational steps (Fig. 6.10b):

1. Based on values already calculated in the modular subroutine REGION, for the detailed geometric properties of the cross sections IC = 1, ..., NC, which are passed to the subroutine through the labeled COMMON/GEOEST/, BOTTOM calculates all the required interpolated values for the detailed geometric properties of the cross sections (Sect. 3.3.1) in each element IX.
2. Based on already calculated values of the channel flow rates GFX(IMX) in the upstream half-element IMX = 2*IX − 1 and GFX(IPX) in the downstream half-element IPX = 2*IX, which are passed to the subroutine through the labeled COMMON/GFXSOL/, BOTTOM calculates the interpolated value for the channel flow rate GFXIII in the element IX [Eq. (3.5b)].
3. BOTTOM determines the computational values of the radionuclide concentrations in the element IX, consisting of

    a. CRWIII = CRW(IX) as the water concentration of the radionuclide in the water layer in the element IX, which is passed to the subroutine through the labeled COMMON/CRWSOL/, and
    b. CRBIII = CRB(IX) as the bottom concentration of the radionuclide in the bottom layer in the element IX, which is passed to the subroutine through the labeled COMMON/CRBSOL/.

4. Based on already calculated values for the cross-sectional area ARXIII and the channel flow rate GFXIII in the element IX, BOTTOM calculates the VLXABS as the absolute value of channel flow velocity in the element IX [Eq. (3.7b)].
5. BOTTOM calculates the sets of parameters required for the formulation of the bottom radionuclide transport fluxes (Sect. 3.5) at the common bottom enclosure surface that separates the water layer from the bottom layer in the element IX. The set of parameters consists of

   a. REYNUM as the Reynolds number [Eq. (3.39)] in the element IX,
   b. ETRTRB as the part of the local, isotropic, coefficient of eddy-turbulent transport at the bottom of the main flow channel, which depends on the velocity conditions in the main flow channel, represented by the Reynolds number REYNUM [Eqs. (3.39), (3.58)-(3.60), and (3.72)] in the element IX,
   c. ETRBOT as the effective coefficient of eddy-turbulent radionuclide transport used in the formulation of the bottom-mixing radionuclide transport flux [Eq. (3.72)] in the element IX, and
   d. VFRBOT as the local, bottom shear velocity associated with the representation of the bottom shear stress conditions at the bottom of the water layer [Eqs. (3.79a) and (3.79b)] in the element IX.

6. BOTTOM calculates GRFALL as the contribution of the bottom-settling radionuclide transport flux [Eq. (3.74)] to the net bottom radionuclide transport flux [Eq. (3.71)] at the common bottom enclosure surface, between the water layer and the bottom layer, in the element IX.
7. BOTTOM calculates GRSUSP as the contribution of the bottom-resuspension radionuclide transport flux [Eq. (3.79)] to the net bottom radionuclide transport flux [Eq. (3.71)] at the common bottom enclosure surface, between the water layer and the bottom layer, in the element IX.
8. BOTTOM calculates GRDDIF as the contribution of the bottom-mixing radionuclide transport flux [Eq. (3.72)] to the net bottom radionuclide transport flux [Eq. (3.71)] at the common bottom enclosure surface, between the water layer and the bottom layer, in the element IX.
9. BOTTOM calculates the net bottom radionuclide transport flux GRDCRW = −GRFALL + GRSUSP + GRDDIF [Eq. (3.80)] (along the geophysical vertical z-axis), from the bottom layer into the water layer, at the common bottom enclosure surface, between the water layer and the bottom layer, in the element IX.
10. BOTTOM assigns the net bottom radionuclide transport flux GRDCRB = −GRDCRW [Eq. (3.81)] (along the geophysical vertical z-axis), from the water layer into the bottom layer, at the common bottom enclosure surface, between the water layer and the bottom layer, in the element IX.

The final part of the computation stage completes the fourth step of the successive updating scheme [Eqs. (5.26a) and (5.26b)] used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code by calculating the terms representing the contribution of the net bottom radionuclide transport effects, between the water layer and the bottom layer, to the right-hand-side solution functions of the radionuclide concentrations in each element, according to the following two operational steps (Fig. 6.10b):

11. BOTTOM calculates, at each intermediate time level T, the part representing the contribution of the net bottom radionuclide transport effect, from the bottom layer into the water layer [Eq. (5.26a)], as the additional term to the value of the right-hand-side solution function (slope) FNCCRW(IX), which is stored in the labeled COMMON/CRWSOL/, for the solution of water concentration of the radionuclide in the water layer CRW(IX) in the element IX [Eq. (5.4a)].

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12. **BOTTOM calculates, at each intermediate time level T, the part representing the contribution of the net bottom radionuclide transport effect, from the water layer into the bottom layer [Eq. (5.26b)], as the additional term to the value of the right-hand-side solution function (slope) FNCCRB(IX), which is stored in the labeled COMMON/CRBSOL/, for the solution of bottom concentration of the radionuclide in the bottom layer CRB(IX) in the element IX [Eq. (5.5a)].**

At the end of the computation stage, BOTTOM completes the calculations, at the intermediate time level T, for all the terms associated with the contribution of the bottom radionuclide transport (along the geophysical vertical z-axis), between the water layer and the bottom layer, which represents the fourth step in the computational construction of the right-hand-side solution functions of the principal solution variables in all the elements, according to the successive updating scheme, used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code; then, it returns to the modular subroutine SOLVER.

6.11 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE SURFAC

The modular subroutine SURFAC represents the computational algorithm for formulating the contribution of transport on the water surface to the solution of flow and radionuclide concentration conditions in the NX number of elements and 2*NX number of half-elements, according to the one-dimensional formulation of the discrete-element model of the RADONE computer code (Sects. 2, 3.7, 4.4, 4.5, and 5.2). SURFAC is the fifth of eight major modular subroutines that are called by the computational procedure of the modular subroutine SOLVER, according to the sequential computational method [Eqs. (5.27a)–(5.27d)], based on the successive updating scheme for the solution of 4*NX number of right-hand-side solution functions, consisting of (1) $[F_{SRF}(\overline{H})]_i$ in all N elements [Eqs. (5.8) and (5.27a)], (2) $[F_{SRF}(\overline{G}_x)]_{i-1/4}$ in all N upstream half-elements [Eqs. (5.14) and (5.27b)], (3) $[F_{SRF}(\overline{G}_x)]_{i+1/4}$ in all N downstream half-elements [Eqs. (5.20) and (5.27c)], and (4) $[F_{SRF}(\overline{C}_{rw})]_i$ in all N elements [Eqs. (2.9) and (5.27d)].

SURFAC represents the computational procedure associated with the formulation of the effects of detailed rainfall, wind, and radionuclide concentration conditions, which depend on the climatological conditions in the geographic region, on the flow and on the concentration of the radionuclide in the water layer in the main flow channel of a river or an estuary.

The formulation of momentum transport and radionuclide transport conditions at the water surface can consider detailed temporal variations of rainfall and wind conditions, based on already available information from various weather stations in the geographic (climatological) region of the main flow channel of the river or estuary (Sects. 3.7, 4.4, and 4.5). The formulation of the radionuclide transport submodel for the water surface considers radionuclide concentrations as dissolved in the rainwater. Hence, the formulation of the radionuclide transport conditions at the water surface can also consider detailed temporal variations of the water concentration of the radionuclide in the rainfall, based on the detailed temporal variations of the climatological conditions and the available information about the temporal variations of radionuclide concentrations in the atmosphere above the geographic (climatological) region of the main flow channel of the river or estuary.

The present version of the modular subroutine SURFAC of the RADONE computer code does not include provisions for incorporating spatial variations of the climatological conditions and the concentration conditions of the radionuclide in the rainfall along the curvilinear longitudinal x-axis of the main flow channel (Sects. 4.4 and 4.5). The computation procedure of SURFAC considers only the temporal variations of weather conditions and radionuclide concentration conditions in the rainfall in the overall geographic (climatological) region of the main flow channel (Sect. 4.5), based on averaging of the available local information from various weather stations and other sources located in the geographic region of a river or an estuary.

The structure and computational procedure of SURFAC (Figs. 6.11a–6.11c) consist of two operational stages, the preparation stage and the computation stage, which are initiated and completed, depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.11.1 Preparation Stage

SURFAC is first called from the MAIN program, with the value of the integer control parameter KRUN = 0 (Fig. 6.2), which is passed to the subroutine through the labeled COMMON/CONTRL/.

SURFAC first reads (Fig. 6.11a) the specified input data (Sect. 7.10) for the value of the integer control parameter ICNSUR, which represents the user-specified option for excluding or including the contribution of transport at the water surface to the solution of principal solution variables in the main flow channel (Sect. 6.5). The specified value of the integer control parameter ICNSUR is stored in the labeled COMMON/CALLER/, and it is passed to the modular subroutine SOLVER (Sect. 6.5).

For the value of the integer control parameter ICNSUR = 0, which represents the user-specified option for excluding the contribution of transport at the water surface to the solution of principal solution variables in the main flow channel (Sect. 6.5), SURFAC returns to the MAIN program without any additional operational step (Fig. 6.11a) because it does not need to read any additional specified input data.

For the value of the integer control parameter ICNSUR = 1 (or > 0), which represents the user-specified option for including the contribution of transport at the water surface to the solution of principal solution variables in the main flow channel (Sect. 6.5), SURFAC initiates the first part of the preparation stage (Fig. 6.11a) for specifying internally the constant values of the coefficients and parameters used in the formulation of the nonconvective transport model for the water surface (Sects. 3.7, 4.4, and 4.5), according to the following operational step:

1. SURFAC specifies the constant values for
   a. BGRAIN = 100 ft/h as the specified constant coefficient associated with the formulation of the overall effect of increasing wind shear stress due to the increasing effective density of air-water mixture in the wind with the increasing rainfall rate per unit area in the geographic (climatological) region of the main flow channel [Eq. (3.90)],
   b. CWRAIN = 0.4 as the specified constant for calculating the approximate rainfall velocity (along the curvilinear longitudinal x axis of the main flow channel) at the water surface as a percentage of the wind velocity (along the curvilinear longitudinal x-axis of the main flow channel) at the location of the center of the element IX of the main flow channel [Eq. (4.49)],
   c. COFWND = 0.0026 as the specified constant surface-wind friction coefficient associated with the formulation of surface wind stress [Eq. (3.90)], and
   d. DCRDRN = 0 as the specified zero constant for approximately representing the difference between the water concentration of the radionuclide in the rainfall and the water concentration of the radionuclide in the drainage flow into the main flow channel [Eqs. (2.9) and (4.54)].

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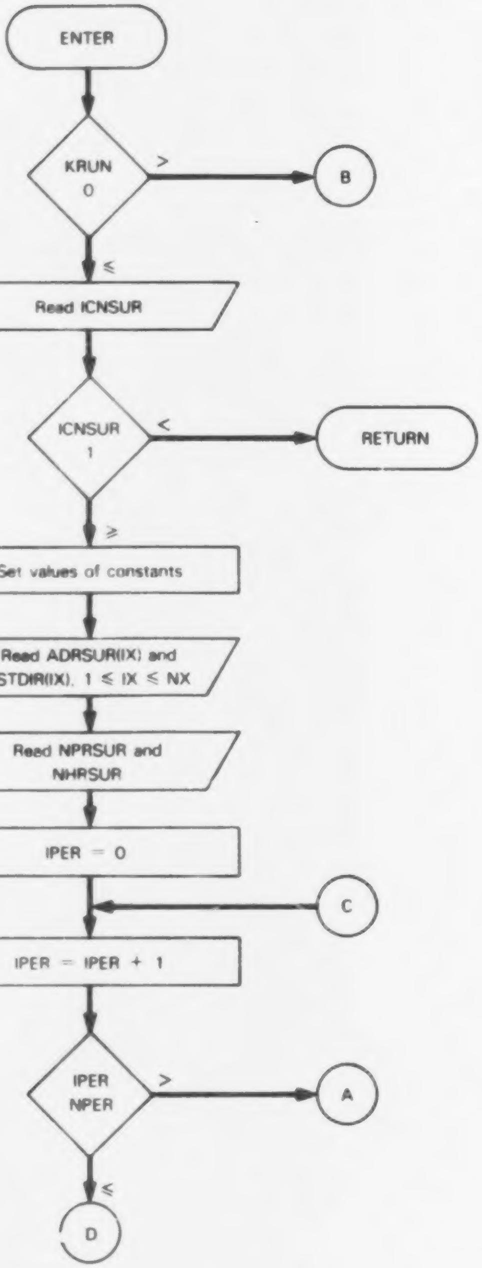
ENTER
KRUN
0
>
B
≤
Read ICNSUR
ICNSUR
1
<
RETURN
≥
Set values of constants
Read ADRSUR(IX) and
ESTDIR(IX), 1 ≤ IX ≤ NX
Read NPRSUR and
NHRSUR
IPER = 0
C
IPER = IPER + 1
IPER
NPER
>
A
≤
D

Fig. 6.11a. Abbreviated flowchart of the structure and computational procedure of the modular subroutine SURFAC of the RADONE computer code.

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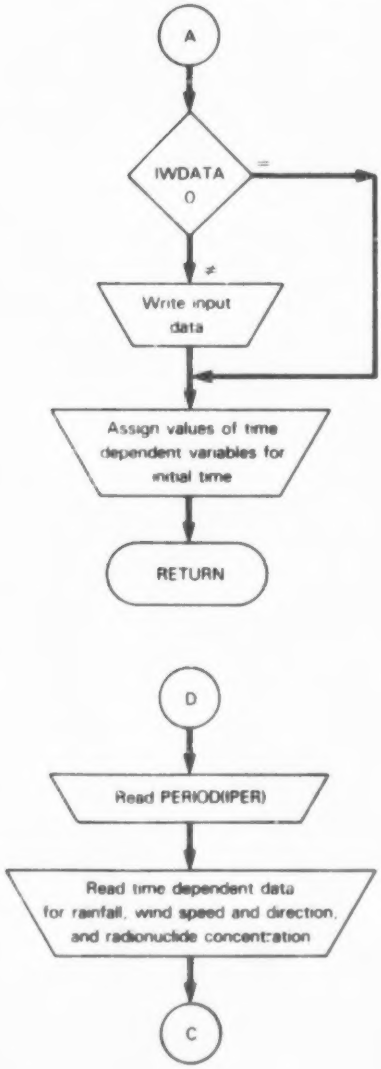
A
IWDATA
0
=
≠
Write input data
Assign values of time dependent variables for initial time
RETURN
D
Read PERIOD(IPER)
Read time dependent data for rainfall, wind speed and direction, and radionuclide concentration
C

Fig. 6.11b. Abbreviated flowchart of the structure and computational procedure of the modular subroutine SURFAC of the RADONE computer code (continued).

The second part of the preparation stage of SURFAC reads the specified input data for geometric conditions of the main flow channel, which are associated with the formulation of transport at the water surface and transport by drainage flow from the banks of the main flow channel (Sects. 3.7, 4.4, and 4.5), according to the following operational step (Fig. 6.11a):

2. SURFAC reads and stores, in the labeled COMMON/ESTCON/ (Appendix A), the set of specified input data for the geometric conditions of the main flow channel in all elements IX = 1, ..., NX (Sects. 4.4 and 7.9). This data set consists of

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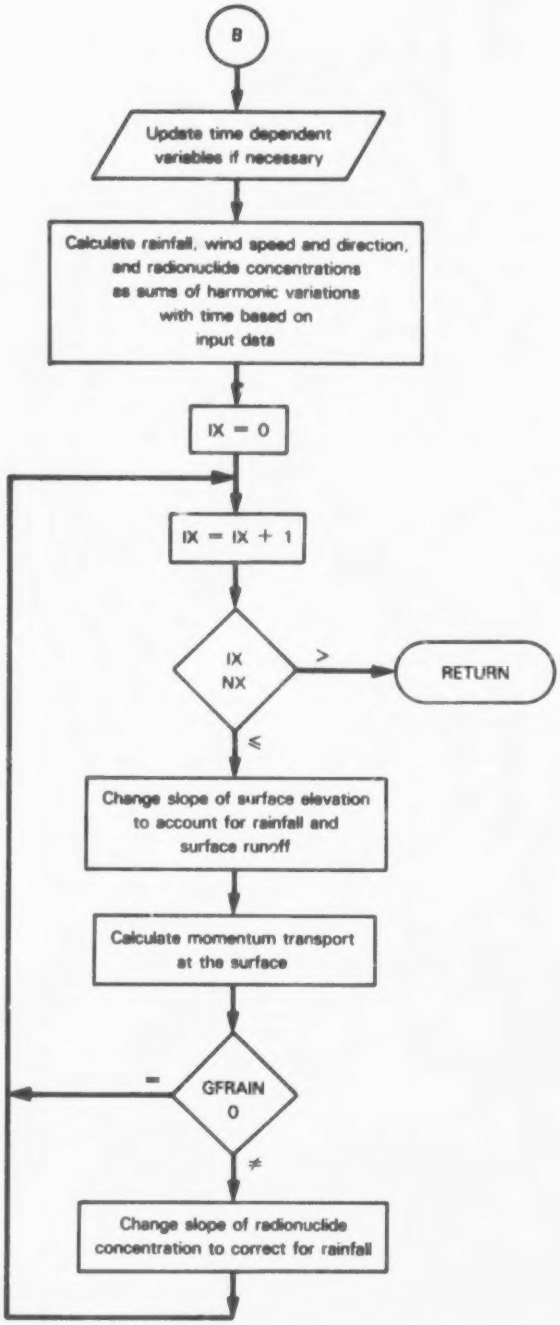
B
Update time dependent variables if necessary
Calculate rainfall, wind speed and direction, and radionuclide concentrations as sums of harmonic variations with time based on input data
IX = 0
IX = IX + 1
IX
NX
>
RETURN
≤
Change slope of surface elevation to account for rainfall and surface runoff
Calculate momentum transport at the surface
GFRAIN
0
=
≠
Change slope of radionuclide concentration to correct for rainfall

Fig. 6.11c. Abbreviated flowchart of the structure and computational procedure of the modular subroutine SURFAC of the RADONE computer code (continued).

a. ADRSUR(IX) as the specified drainage area in the geographic (climatological) region associated with drainage flow into the element IX of the main flow channel [Eq. (4.43)] and

b. ESTDIR(IX) as the specified temporally constant angle of the direction of the curvilinear longitudinal *x*-axis of the main flow channel in the element IX relative to an arbitrarily specified geographic coordinate system that is also used for specifying the direction of the wind in the geographic (climatological) region of the main flow channel [Eq. (4.42)].

The third part of the preparation stage of SURFAC reads the specified input data about the spatially averaged (1) weather information and (2) information about the water concentration of the radionuclide in the rainfall (Sect. 4.5) that is representative of the atmospheric conditions in the geographic (climatological) region containing the main flow channel of the river or estuary, according to the following two operational steps (Figs 6.11a and 6.11b):

3. SURFAC reads the specified input data (Sect. 7.10) for

   a. NPER as the specified number of time periods for formulating the nonharmonic variations (or temporally uniform conditions) of the atmospheric (climatological) conditions in the geographic region (Sect. 4.5) and

   b. NHRT as the specified number (maximum of two) of harmonics (cosine) for formulating the short-term (within 1 d) harmonic variations of the atmospheric (climatological) conditions in the geographic region [Eqs. (4.44)–(4.46) and (4.53)].

At least one time period (i.e., NPER $\geqslant 1$) and at least one harmonic (i.e., NHRT $\geqslant 1$) are required for specifying the variations of atmospheric (climatological) conditions in the geographic region. The harmonic variation of any specified atmospheric (climatological) condition can be eliminated by considering the amplitude of the harmonic variation as zero in the formulation of the short-term (within 1 d) variation of the particular climatological condition in the geographic region.

4. SURFAC reads the specified input data as IPER = 1, ..., NPER list of records (Sect. 7.10) for the durations of the time periods (Sect. 4.5) and the detailed information for the weather conditions (rainfall and wind conditions) and the conditions for water concentration of the radionuclide in the rainfall in the geographic (climatological) region during the specified time periods as

   a. the specified input data for rainfall conditions, which are stored in the labeled COMMON/GRNCON/ (Appendix A), consisting of

      (1) GRNAVG(IPER) as the specified input data for the average rainfall rate (per unit area) in the geographic (climatological) region of the main flow channel, for the specified time period PERIOD(IPER) [Eq. (4.44)],

      (2) GRNVAR(IPER,IHRT = 1,2) as the specified input data for the amplitude of the IHR harmonic (cosine) of the difference in rainfall rate (per unit area), for the specified time period PERIOD(IPER); used to represent the short-term variation of rainfall rate from the specified average rainfall rate during the specified time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.44)],

      (3) PERGRN(IPER,IHRT = 1,2) as the specified input data for the period of the IHRT harmonic (cosine) of the difference in rainfall rate (per unit area), for the specified time period PERIOD(IPER); used to represent the short-term variation of rainfall rate from the specified average rainfall rate during the specified time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.44)], and

(4) TLGGRN(IPER,IHRT = 1,2) as the specified input data for the lag time of the IHRT harmonic (cosine) of the difference in rainfall rate (per unit area), for the specified time period PERIOD(IPER); used to represent the short-term variation of rainfall rate from the specified average rainfall rate during the specified time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.44), hour of the day relative to midnight];

b. the specified input data for wind speed conditions, which are stored in the labeled COMMON/WNDCON/ (Appendix A), consisting of

(1) WNDAVG(IPER) as the specified input data for the average wind speed in the geographic (climatological) region of the main flow channel, for the specified time period PERIOD(IPER) [Eq. (4.45)],
(2) WNDVAR(IPER,IHRT = 1,2) as the specified input data for the amplitude of the IHRT (cosine) harmonic of the difference in wind speed, for the specified time period PERIOD(IPER); used to represent the short-term variation of wind speed from the specified average wind speed during the time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.45)],
(3) PERWND(IPER,IHRT = 1,2) as the specified input data for the period of the IHRT harmonic (cosine) of the difference in wind speed, for the specified time period PERIOD(IPER); used to represent the short-term variation of wind speed from the specified average wind speed during the specified time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.45)], and
(4) TLGWND(IPER,IHRT = 1,2) as the specified input data for the lag time of the IHRT harmonic (cosine) of the difference in wind speed, for the specified time period PERIOD(IPER); used to represent the short-term variation of wind speed from the specified average wind speed during the specified time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.45), hour of the day relative to midnight];

c. the specified input data for wind-direction conditions, which are stored in the labeled COMMON/WNDCON/ (Appendix A), consisting of

(1) DIRAVG(IPER) as the specified input data for the average wind direction (relative to an arbitrarily specified geographic reference coordinate system) in the geographic (climatological) region of the main flow channel, for the specified time period PERIOD(IPER) [Eq. (4.46)],
(2) DIRVAR(IPER,IHRT = 1,2) as the specified input data for the amplitude of the IHRT harmonic (cosine) of the difference in wind direction (relative to an arbitrarily specified geographic reference coordinate system), for the specified time period PERIOD(IPER); used to represent the short-term variation of wind direction from the specified average wind direction during the specified time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.46)],
(3) PERDIR(IPER,IHRT = 1,2) as the specified input data for the period of the IHRT harmonic (cosine) of the difference in wind direction (relative to an arbitrarily specified geographic reference coordinate system), for the specified time period PERIOD(IPER); used

to represent the short-term variation of wind direction from the specified average wind direction during the specified time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.46)], and

(4) TLGDIR(IPER,IHRT = 1,2) as the specified input data for the lag time of the IHRT harmonic (cosine) of the difference in wind direction (relative to an arbitrarily specified geographic reference coordinate system), for the specified time period PERIOD(IPER); used to represent the short-term variation of wind direction from the specified average wind direction during the specified time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.46), hour of the day relative to midnight]; and

d. the specified input data for water concentration of the radionuclide in the rainfall, which are stored in labeled COMMON/CRDCON/ (Appendix A), consisting of

(1) CRDAVG(IPER) as the specified input data for the average water concentration of the radionuclide in the rainfall in the geographic (climatological) region of the main flow channel, for the specified time period PERIOD(IPER) [Eq. (4.53)],

(2) CRDVAR(IPER,IHRT = 1,2) as the specified input data for the amplitude of the IHRT harmonic (cosine) of the difference in water concentration of the radionuclide in the rainfall, for the specified time period PERIOD(IPER); used to represent the short-term variation of water concentration of the radionuclide in the rainfall from the specified average water concentration of the radionuclide in the rainfall during the specified time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.53)],

(3) PERCRD(IPER,IHRT = 1,2) as the specified input data for the period of the IHRT harmonic (cosine) of the difference in water concentration of the radionuclide in the rainfall, for the specified time period PERIOD(IPER); used to represent the short-term variation of water concentration of the radionuclide in the rainfall during the specified time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.53)], and

(4) TLGCRD(IPER,IHRT = 1,2) as the specified input data for the lag time of the IHRT harmonic (cosine) of the difference in water concentration of the radionuclide in the rainfall, for the specified time period PERIOD(IPER); used to represent the short-term variation of water concentration of the radionuclide in the rainfall during the specified time period PERIOD(IPER) in the geographic (climatological) region of the main flow channel [Eq. (4.53), hour of the day relative to midnight].

It is important that extensive specified input data sets for SURFAC are required only for long-term and accurate representations of the temporal variations of the climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel for obtaining long-term and accurate simulations of the flow conditions and radionuclide concentration conditions in a river or an estuary, by the RADONE computer code. For simulations with simplified climatological conditions and radionuclide concentration conditions, as approximately uniform values in the geographic region of the main flow channel, a single-record specified data set, with IPER = NPER = 1, would be sufficient for representations of long-term nonharmonic conditions. Furthermore, for simulations that do not require the consideration of short-term (within 1 d) harmonic variations of climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel, a single harmonic, with IHR =

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NHRT = 1, and with zero values for the amplitudes of the first harmonics of all the climatological conditions and radionuclide concentration conditions, would be sufficient for eliminating all the short-term (within 1 d) harmonic variations of the climatological conditions. Hence, although SURFAC includes all the necessary capabilities for incorporating detailed information about climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel, based on extensive specified input data sets, it also includes provisions to allow the user to implement the RADONE computer code based on simplified climatological conditions and radionuclide concentration conditions that require only simple specified input data sets with a very limited number of data records.

The fourth part of the preparation stage of SURFAC consists of the following operational step (Fig. 6.11b):

5. For the value of the integer control parameter IWDATA = 1, which is read in the MAIN program (Sect. 6.2) and passed through the labeled COMMON/PUTOUT/, SURFAC writes as printed output (Sect. 8.9) all the specified input data for climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel (Sect. 4.5).

The fifth part of the preparation stage of SURFAC also includes special features that enable the user to implement the RADONE computer code with minimal amount of effort in simulating accurately the detailed flow conditions and radionuclide concentration conditions, in an actual controlled river or a tidal estuary, based on extensive specified input data for climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel. The structure and the computational procedure of SURFAC include special provisions for aligning the time periods of the specified input data for climatological conditions and radiological concentration conditions in the geographic region of the main flow channel with the internally calculated time levels of the solution, according to the general computational algorithm of the RADONE computer code. Hence, if the user already has extensive sets of specified input data for climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel for a long overall period (e.g., one week, one month, or one year) with a large number of specified time periods (Sect. 4.5) for representing the short-term variations (e.g., 1 hour, 1 day, or 1 week), the computer simulations with the RADONE computer code can be started at any time within the overall period of the available data, without requiring any modification of the extensive sets of specified input data. The internal computational algorithm of the preparation stage of SURFAC automatically aligns the specified initial time (Sect. 6.4) with the appropriate specified time period of the specified input data for climatological and radionuclide concentration conditions in the geographic region of the main flow channel. The detailed discussion of the special computational procedure for aligning the time periods of the specified input data for the climatological conditions in the geographic region of the main flow channel with the internally calculated time level of the solution is presented in the users manual of the ESTONE computer code [Eraslan (1983)] which includes a more extensive modular subroutine SURFAC for specifying the transport conditions at the water surface of the main flow channel of a controlled river or a tidal estuary. Therefore, the discussions of the fifth part of the preparation stage of SURFAC will be presented in a summary form in this report, in order to avoid extensive repetition of the same procedure which is common to the two computer codes of the UTA project [e.g., Eraslan et al. (1976), Eraslan and Witten (1984)]. Hence, in summary form, the fifth part of the preparation stage of SURFAC initiates and completes the necessary procedure for determining the appropriate specified time period and the specified input data for the climatological conditions and radionuclide concentration conditions that correspond to the specified initial time (Sect. 6.4), according to the following operational steps (Fig. 6.11b):

6. For the specified initial time T, which is read in the modular subroutine INITAL (Sect. 6.4) and passed through the labeled COMMON/CONTRL/, SURFAC determines the appropriate specified time period for the climatological conditions and radionuclide concentration conditions PERIOD(IPER), which includes the initial time T (Sect. 4.5).
7. SURFAC determines the nonharmonic average values of the climatological conditions in the geographic region of the main flow channel, at the specified initial time T (Sect. 4.5).
8. SURFAC determines the nonharmonic average value of the water concentration of the radionuclide in the rainfall in the geographic region of the main flow channel, at the specified initial time T (Sect. 4.5).
9. SURFAC determines, for all the harmonics IHRT = 1, ..., NHRT, (a) the amplitude, (b) the period, and (c) the lag time of the IHRT harmonic of the difference of each climatological condition used to represent the short-term variation of the climatological condition from the specified average value of the climatological condition in the geographic region of the main flow channel, at the specified initial time T (Sect. 4.5).
10. SURFAC determines, for all the harmonics IHRT = 1, ..., NHRT, (a) the amplitude, (b) the period, and (c) the lag time of the IHRT harmonic of the difference of the water concentration of the radionuclide in the rainfall used to represent the short-term variation of the water concentration of the radionuclide in the rainfall from the specified average value of the water concentration of the radionuclide in the rainfall in the geographic region of the main flow channel, at the specified initial time T (Sect. 4.5).

At the end of the preparation stage, SURFAC completes all the necessary initialization procedures that would be required in the subsequent computation stage of the subroutine; then, it returns to the MAIN program.

6.11.2 Computation Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of the RADONE computer code, SURFAC is called by the modular subroutine SOLVER at every intermediate time level of the numerical integration (solution) of the governing system of discrete-element equations of the mathematical transport model (Sect. 5).

The first part of the computation stage of SURFAC determines the appropriate time period and the specified input data for climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel that correspond to the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, according to the following operational steps (Fig. 6.11c):

1. Based on the value of the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, SURFAC determines the appropriate specified time period for the specified climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel PERIOD(IPER). If the intermediate time level T extends beyond the specified time corresponding to the end of the last input record for the specified time period PERIOD(NPER), SURFAC automatically retains the last specified time period PERIOD(IPER); and it determines the climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel based on the specified input data for the last specified time period PERIOD(NPER = NPRSUR).

2. SURFAC determines the nonharmonic average values of the climatological conditions in the geographic region of the main flow channel, at the intermediate time level T.
3. SURFAC determines the nonharmonic average value of the water concentration of the radionuclide in the rainfall in the geographic region of the main flow channel, at the intermediate time level T.
4. SURFAC determines, for all the harmonics IHRT = 1, ..., NHRT, (a) the amplitude, (b) the period, and (c) the lag time of the IHRT harmonic of the difference of each climatological condition used to represent the short-term variation of the climatological condition from the specified average value of the climatological condition in the geographic region of the main flow channel, at the intermediate time level T.
5. SURFAC determines, for all the harmonics IHRT = 1, ..., NHRT, (a) the amplitude, (b) the period, and (c) the lag time of the IHRT harmonic of the difference of the water concentration of the radionuclide in the rainfall used to represent the short-term variation of the water concentration of the radionuclide in the rainfall from the specified average value of the water concentration of the radionuclide in the rainfall in the geographic region of the main flow channel, at the intermediate time level T.

The second part of the computation stage of SURFAC calculates, at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, the climatological conditions and radionuclide concentration conditions, based on specified input data for the average values and for all the harmonic variations, IHRT = 1, ..., NHRT, of the climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel, according to the following operational steps (Fig. 6.11c):

6. SURFAC calculates the final updated value of rainfall rate GFRAIN at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/. This calculation is based on

   a. the average rainfall rate, which was previously set as GFRAIN,
   b. the amplitudes of the harmonics (cosine) for the variation of rainfall rate DHTGRN(IHRT),
   c. the periods of the harmonics (cosine) for the variation of rainfall rate GRNPER(IHRT), and
   d. the lag times of the harmonics (cosine) for the variation of rainfall rate TTLGRN(IHRT) in the geographic (climatological) region of the main flow channel [Eq. (4.44)].

7. SURFAC calculates the final updated value of wind speed WNDVEL at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/. This calculation is based on

   a. the average wind speed, which was previously set as WNDVEL,
   b. the amplitudes of the harmonics (cosine) for the variation of wind speed DHTWND(IHRT),
   c. the periods of the harmonics (cosine) for the variation of wind speed WNDPER(IHRT), and
   d. the lag times of the harmonics (cosine) for the variation of wind speed TTLWND(IHRT) in the geographic (climatological) region of the main flow channel [Eq. (4.45)].

8. SURFAC calculates the final updated value of wind direction WINDIR at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/. This calculation is based on

  a. the average wind direction, which was previously set as WINDIR,
  b. the amplitudes of the harmonics (cosine) for the variation of wind direction DHTDIR(IHRT),
  c. the periods of the harmonics (cosine) for the variation of wind direction DIRPER(IHRT), and
  d. the lag times of the harmonics (cosine) for the variation of wind direction TTLDIR(IHRT) in the geographic (climatological) region of the main flow channel [Eq. (4.46)].

9. SURFAC calculates the final updated value of the water concentration of the radionuclide in the rainfall CRDGRN at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/. This calculation is based on

  a. the average value of water concentration of the radionuclide in the rainfall, which was previously set as CRDAIR,
  b. the amplitudes of the harmonics (cosine) for the variation of the water concentration of the radionuclide in the rainfall DHTCRD(IHRT),
  c. the periods of the harmonics (cosine) for the variation of the water concentration of the radionuclide in the rainfall CRDPER(IHRT), and
  d. the lag times of the harmonics (cosine) for the variation of the water concentration of the radionuclide in the rainfall TTLCRD(IHRT) in the geographic (climatological) region of the main flow channel [Eq. (4.53)].

The third part of the computation stage of SURFAC calculates, at each intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, the terms associated with the geometrical properties of the elements and with the transport conditions at the water surface that depend only on the already determined climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel according to the following operational steps:

10. Based on values already calculated, in modular subroutine REGION, for the detailed geometric properties of the cross sections IC = 1, ..., NC, which are passed to the subroutine through the labeled COMMON/GEOEST/, SURFAC calculates all the required linearly interpolated values for the detailed geometric properties of the cross sections (Sect. 2.3.1) at three locations in each element. These locations are (a) in the upstream half-element IMX = 2*IX − 1, (b) in the element III = IX, and (c) in the downstream half-element IPX = 2*IX.
11. SURFAC calculates conditions at the water surface that are affected by the rainfall. These conditions consist of

  a. FFRWND as the auxiliary coefficient that includes the effect of increasing wind stress, on the water surface of the main flow channel, due to the increasing effective density of the air-water mixture in the wind under rainfall conditions [Eq. (3.90)],
  b. VLXWRN as the rainfall velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) in the element IX [Eqs. (2.2) and (2.3)], which is assumed to be the same value for rainfall velocity in both the upstream half-element IMX = 2*IX − 1 and the downstream half-element IPX = 2*IX, and
  c. VLXDRN = 0 as the negligible drainage flow velocity in the element IX [Eqs. (2.2), (2.3), and (4.50)], which is assumed to be the same value for drainage flow velocity in both the upstream half-element IMX = 2*IX − 1 and the downstream half-element IPX = 2*IX.

12. SURFAC calculates FSRIMX as the contribution of surface wind stress (along the curvilinear longitudinal *x*-axis of the main flow channel) in the upstream half-element IMX = 2*IX − 1 [Eqs. (2.2) and (3.90)].
13. SURFAC calculates FSRIPX as the contribution of surface wind stress (along the curvilinear longitudinal *x*-axis of the main flow channel) in the downstream half-element IPX = 2*IX [Eqs. (2.3) and (3.90)].

The fourth part of the computation stage of SURFAC completes the fifth step of the successive updating scheme [Eqs. (5.27a)–(5.27d)] used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code by calculating the terms representing the contributions of transport at the water surface to the right-hand-side solution functions for the solution of the principal flow variables in each element and half-element, according to the following operational steps (Fig. 6.11c):

14. SURFAC calculates, at each intermediate time level T, the part representing the water mass transport at the water surface into the main flow channel, which also includes the water mass transport associated with drainage flow into the main flow channel [Eq. (5.27a)], as the additional term to the value of the right-hand-side solution function (slope) FNCHSR(IX), which is stored in the labeled COMMON/HSRSOL/, for the solution of water surface elevation HSR(IX) in the element IX [Eq. (5.1a)].
15. SURFAC calculates, at each intermediate time level T, the part representing the momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) at the water surface into or out of the main flow channel [Eq. (5.27b)], with negligible momentum associated with the drainage flow into the main flow channel [Eq. (4.50)], as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IMX), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IMX) in the upstream half-element IMX = 2*IX − 1 [Eq. (5.2a)].
16. SURFAC calculates, at each intermediate time level T, the part representing the momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) at the water surface into or out of the main flow channel [Eq. (5.27c)], with negligible momentum associated with drainage flow into the main flow channel [Eq. (4.50)], as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IPX), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IPX) in the downstream half-element IPX = 2*IX [Eq. (5.3a)].
17. SURFAC calculates, at each intermediate time level T, the combined part, consisting of (a) the radionuclide transport by rainfall at the water surface, with the water concentration of the radionuclide in the rainfall CRDGRN, and (b) the radionuclide transport by drainage flow, with the water concentration of the radionuclide in the drainage flow approximately equal to the water concentration of the radionuclide in the rainfall CRDGRN [Eq. (4.54)], into the main flow channel [Eq. (5.27d)] as the additional term to the value of the right-hand-side solution function (slope) FNCCSL(IX), which is stored in the labeled COMMON/CSLSOL/, for the solution of salinity CSL(IX) in the element IX [Eq. (5.4a)].

At the end of the computation stage, SURFAC completes the calculations, at the intermediate time level T, for all terms associated with transport at the water surface into or out of the main flow channel, which collectively represent the fifth step in the computational construction of all the right-hand-side solution functions for the solutions of all the principal solution variables in all the elements and half-elements, according to the successive updating scheme, used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code; then, it returns to the modular subroutine SOLVER.

The structure and computational procedure of the modular subroutine SURFAC of the advanced development program version of the RADONE computer code were specifically designed to enable the user to understand, without undue difficulty, (1) requirements for the preparation of the specified input data and (2) the computational algorithms associated with the formulations of the relatively complex, temporally varying climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel, which are generally encountered in the applications of the computer code for the assessment of the radiological impact on the receiving water body that would result from accidental radiological release scenarios which can contaminate the part of the atmosphere over the geographic region and the drainage areas in the geographic region of a river or an estuary. Hence, the structure of the modular subroutine SURFAC reads and stores all the specified sets of input data for each time period in the structurally separated part associated with the preparation stage of the subroutine. In certain applications of the RADONE computer code for continuous, long-term, and accurate simulations of flow conditions and radionuclide concentration conditions in a controlled river or a tidal estuary during a relatively long period (e.g., six months), based on specified sets of input data with relatively high temporal resolution (e.g., 1 d or 1 h), SURFAC could require substantial storage. Particularly, in computer systems operating in an interactive, time-sharing mode, this excessive storage requirement of SURFAC could become a problem because excessive core storage allocations to the program could also reduce the overall computational speed of the complete system. This problem can (and should) be avoided by considering successive runs of the RADONE computer code for shorter simulation periods (e.g., one month) and only with the parts of the specified input data sets required for each particular simulation period. Because the RADONE computer code automatically includes the necessary restart capability through the modular subroutine OUTPUT (Sect. 6.15) and the modular subroutine INITAL (Sects. 6.4 and 7.4), the user can (and should) separate the specified sets of input data for a relatively long simulation period (e.g., six months) into partial specified sets of input data for relatively shorter simulation periods (e.g., one month) and apply the code successively by restarting the computations for each successive, relatively shorter simulation period.

The production program version of the RADONE computer code can completely eliminate the storage requirement for the specified sets of input data for each specified time period for the climatological conditions in the geographic region of the main flow channel by combining the preparation stage and the computation stage into a single computation stage in the modular subroutine SURFAC.

6.12 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE STREAM

The modular subroutine STREAM represents the computational algorithm for formulating the contribution of transport associated with stream or tributary flows into or out of the main flow channel to the solution of flow conditions in the NX number of elements and 2*NX number of half-elements, according to the one-dimensional formulation of the discrete-element model of the RADONE computer code (Sects. 2, 4.7, and 5.2). STREAM is the sixth of the eight major modular subroutines that are called by the computational procedure of the modular subroutine SOLVER, according to the sequential computational method [Eqs. (5.28a)–(5.28e)], based on successive updating scheme for the solution of 5*NX number of right-hand-side solution functions, consisting of (1) $[F_{SRM}(\overline{H})]_i$ in all N elements

[Eqs. (5.9) and (5.28a)], (2) $[F_{SRM}(\overline{G}_x)]_{i-1/4}$ in the all N upstream half-elements [Eqs. (5.15) and (5.28b)], (3) $[F_{SRM}(\overline{G}_x)]_{i+1/4}$ in all N downstream half-elements [Eqs. (5.21) and (5.28c)], (4) $[F_{SRM}(\overline{C}_{rw})]_i$ in all N elements [Eqs. (2.10) and (5.28d)], and (5) $[F_{SRM}(\overline{C}_{rb})]_i$ in all N elements [Eqs. (2.19) and (5.28e)].

STREAM represents the computational procedure required for the formulations of the effects of the detailed specified flow conditions and radionuclide concentration conditions associated with the streams or tributaries along the curvilinear longitudinal x-axis of the main flow channel of a river or an estuary. Formulations of the transport conditions associated with streams or tributaries flowing into or out of the main flow channel can consider detailed temporal variations of the principal solution variables based on available information from the gauging stations located on the streams or tributaries in the vicinity of the main flow channel.

The structure and computational procedure of STREAM (Figs. 6.12a–6.12c) consist of two operational stages, the preparation stage and the computation stage, which are initiated and completed depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.12.1 Preparation Stage

STREAM is first called from the MAIN program, with the value of the integer control parameter KRUN = 0 (Fig. 6.2), which is passed to the subroutine through the labeled COMMON/CONTRL/.

STREAM first reads (Fig. 6.12a) the specified input data (Sect. 7.11) for the number of streams or tributaries NSRM = NSTREM that flow into or out of the main flow channel of a river or an estuary. The specified number of streams or tributaries along the main flow channel NSTREM is stored in the labeled COMMON/SRMCON/, and it is passed to the modular subroutine SOLVER (Sect. 6.5).

For the specified input data for NSRM = 0, which corresponds to the case without any streams or tributaries along the main flow channel of the river or estuary, STREAM returns to the MAIN program without any operational step because it does not need to read any additional specified input data.

For the specified input data for NSRM > 0, which corresponds to the case with one or more streams or tributaries along the main flow channel of the river or estuary, STREAM initiates the first part of the preparation stage for reading the specified input data for the locations and control conditions of all streams or tributaries ISRM = 1, ..., NSRM along the main flow channel, according to the following operational steps (Fig. 6.12a):

1. STREAM reads the specified input data (Sect. 7.11) for
   a. [SRMNAM(ISRM,ID), ID = 1,40] as the specified name (with a maximum of 40 letters) of the stream or tributary ISRM along the main flow channel and
   b. NRMPER(ISRM) as the specified number of time periods for formulating the temporal variations (or temporally uniform conditions) of flow conditions from the stream or tributary ISRM flowing into or out of the main flow channel.
2. STREAM reads the specified input data (Sect. 7.11) for
   a. IXCSRM(ISRM) as the specified input data for the element containing the connecting junction of stream or tributary ISRM along the curvilinear longitudinal x-axis of the main flow channel [Eq. (4.65)],

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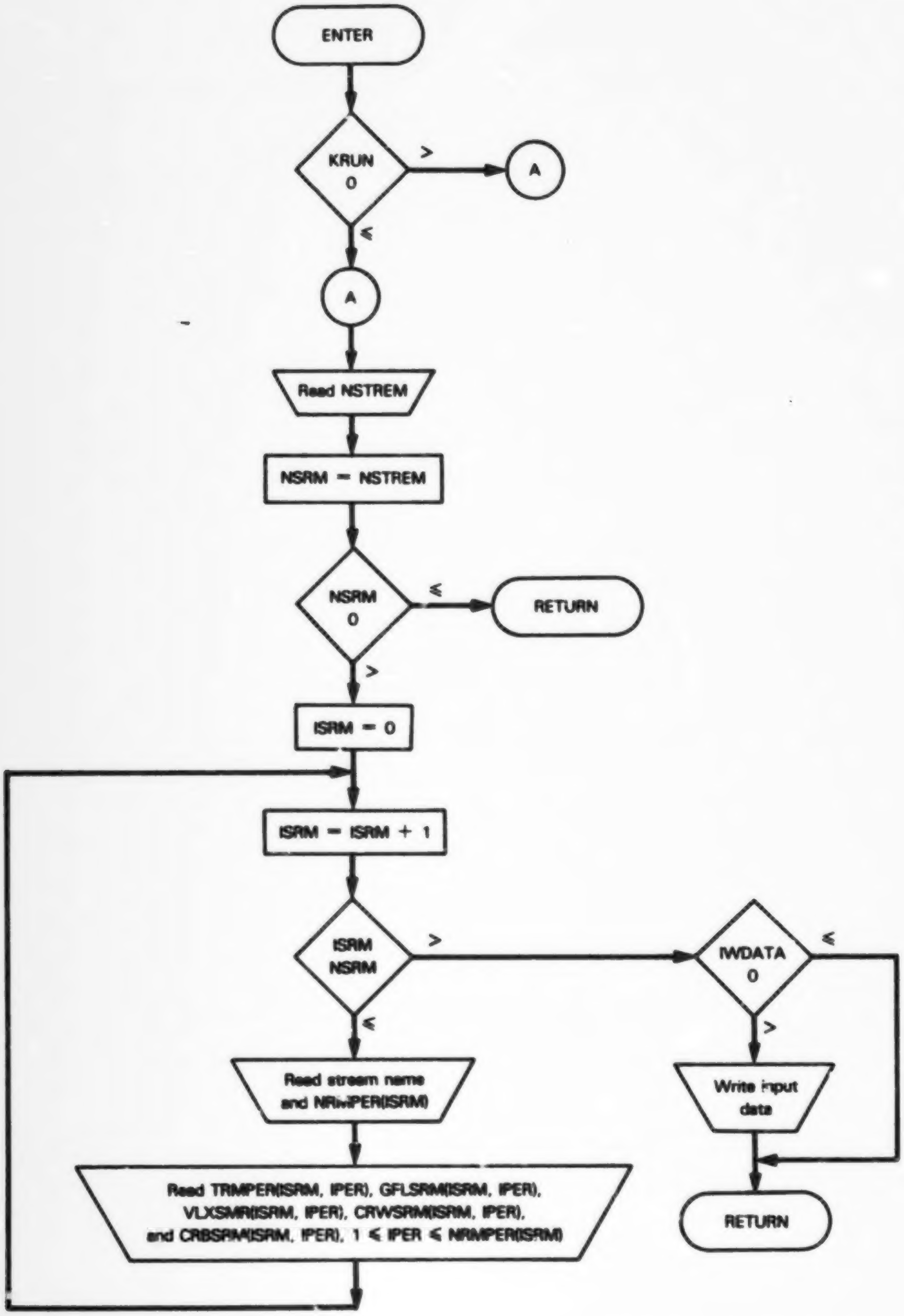
ENTER
KRUN
0
>
A
≤
A
Read NSTREM
NSRM = NSTREM
NSRM
0
≤
RETURN
>
ISRM = 0
ISRM = ISRM + 1
ISRM
NSRM
>
IWDATA
0
≤
>
≤
Read stream name
and NRMPER(ISRM)
Write input
data
Read TRMPER(ISRM, IPER), GFLSRM(ISRM, IPER),
VLXSMR(ISRM, IPER), CRWSRM(ISRM, IPER),
and CRBSRM(ISRM, IPER), 1 ≤ IPER ≤ NRMPER(ISRM)
RETURN

Fig. 6.12a. Abbreviated flowchart of the structure and computational procedure of the modular subroutine STREAM of the RADONE computer code.

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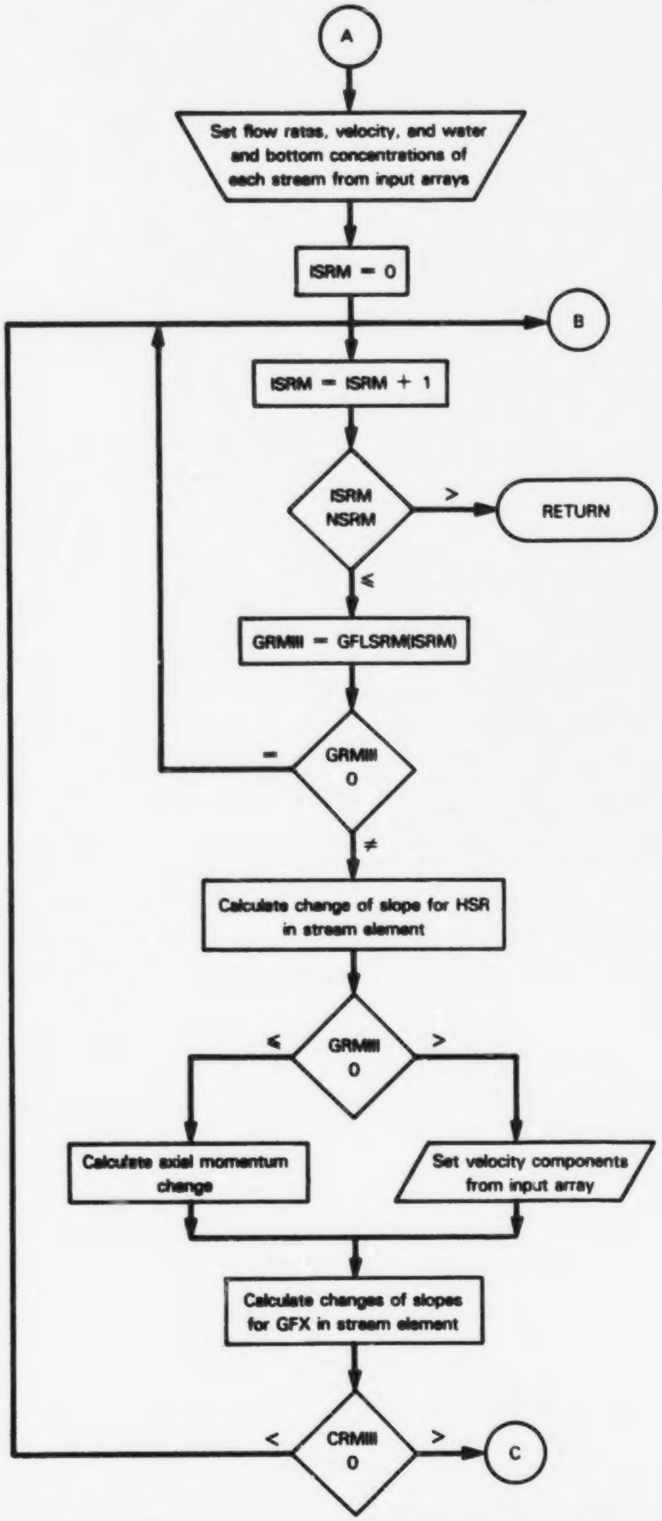
A
Set flow rates, velocity, and water and bottom concentrations of each stream from input arrays
ISRM = 0
B
ISRM = ISRM + 1
ISRM
NSRM
>
RETURN
≤
GRMIII = GFLSRM(ISRM)
=
GRMIII
0
≠
Calculate change of slope for HSR in stream element
≤
GRMIII
0
>
Calculate axial momentum change
Set velocity components from input array
Calculate changes of slopes for GFX in stream element
<
CRMIII
0
>
C

Fig. 6.12b. Abbreviated flowchart of the structure and computational procedure of the modular subroutine STREAM of the RADONE computer code (continued).

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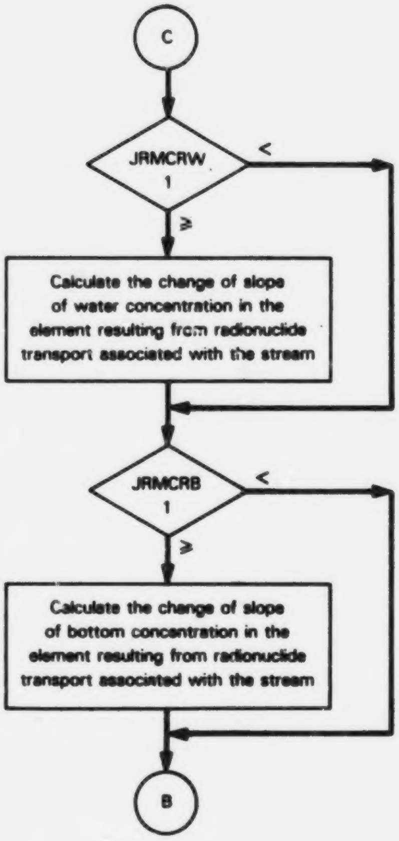
C
JRMCRW
1
<
≥
Calculate the change of slope of water concentration in the element resulting from radionuclide transport associated with the stream
JRMCRB
1
<
≥
Calculate the change of slope of bottom concentration in the element resulting from radionuclide transport associated with the stream
B

Fig. 6.12c. Abbreviated flowchart of the structure and computational procedure of the modular subroutine STREAM of the RADONE computer code (continued).

b. JRMCRW(ISRM) as the specified input data for the temporally constant integer control parameter for determining water concentration of the radionuclide in the flow of the stream or tributary ISRM into the water layer of the main flow channel [Eq. (4.66)], and

c. JRMCRB(ISRM) as the specified input data for the temporally constant integer control parameter for determining bottom concentration of the radionuclide in the flow of the stream or tributary ISRM into the bottom layer of the main flow channel [Eq. (4.67)].

The second part of the preparation stage of STREAM reads, for all streams or tributaries ISRM = 1, ..., NSRM, the specified input data (Sect. 7.10) for the temporal variations of flow conditions in each stream or tributary flowing into or out of the main flow channel, according to the following operational step (Fig. 6.10a):

3. STREAM reads, for each stream or tributary ISRM, the specified set of input data, as IPER = 1, ..., NPER = NRMPER(ISRM) list of records (Sect. 7.10), for durations of the specified time periods (Sect. 4.7) and the detailed specified information about the principal solution variables in the

stream or tributary flowing into or out of the main flow channel, during the specified time periods. This data set consists of

a. TRMPER(ISRM,IPER) as the specified time period of the specified input data for conditions of the flow of stream or tributary ISRM into or out of the main flow channel [Eqs. (4.68)–(4.71)],

b. GFLSRM(ISRM,IPER) as the specified input data for the flow rate of stream or tributary ISRM into or out of the main flow channel, for the specified time period TRMPER(ISRM,IPER) [Eq. (4.68)],

c. VLXSRM(ISRM,IPER) as the specified input data for velocity (along the curvilinear longitudinal x-axis of the main flow channel) of the flow of stream or tributary ISRM into or out of the main flow channel, for the specified time period TRMPER(ISRM,IPER) [Eq. (4.69)],

d. CRWSRM(ISRM,IPER) as the specified input data for the water concentration of the radionuclide in the flow of stream or tributary ISRM into the water layer of the main flow channel, for the specified time period TRMPER(ISRM,IPER) [Eq. (4.70)], and

e. CRBSRM(ISRM,IPER) as the specified input data for the bottom concentration of the radionuclide in the flow of stream or tributary ISRM into the bottom layer of the main flow channel, for the specified time period TRMPER(ISRM,IPER) [Eq. (4.71)].

It is important to point out that extensive specified input data sets for stream or tributary flow conditions are required only for long-term and accurate representations of temporal variations of the principal solution variables in the streams or tributaries flowing into or out of the main flow channel for obtaining long-term and accurate computer simulations of flow conditions and radionuclide concentration conditions in a controlled river or a tidal estuary by the RADONE computer code. For temporally uniform flow conditions and radionuclide concentration conditions in a stream or tributary ISRM, a single-record specified input data set, with IPER = NRMPER(ISRM) = 1, would be sufficient to represent the temporally uniform conditions for principal solution variables in the stream or tributary flowing into the main flow channel. Furthermore, if the necessary information for specifying (1) VLXSRM(ISRM,IPER), (2) CRWSRM(ISRM,IPER), and/or (3) CRBSRM(ISRM,IPER) is not available during any specified time period TRMPER(ISRM,IPER), then the allocated spaces on the data records can be left blank in the preparation of the specified input data sets for the stream or tributary ISRM.

The computation stage of STREAM automatically assumes VLXSRM(ISRM,IPER) = 0 as negligible specified velocity (along the curvilinear longitudinal x-axis of the main flow channel) of the stream or tributary ISRM flowing into the main flow channel for all time.

Also, for JRMCRW(ISRM) = 0 as the user-specified value of the integer control parameter for specifying the conditions of the water concentration of the radionuclide in the flow of stream or tributary ISRM into the water layer of the main flow channel, the computation stage of STREAM automatically neglects the part representing the radionuclide transport associated with the flow of stream or tributary ISRM into the water layer of the main flow channel [Eq. (2.10)], by assuming the water concentration of the radionuclide in the flow of stream or tributary ISRM into the water layer of the main flow channel CRWSRM(ISRM,IPER) = CRW(IX) as the water concentration of the radionuclide in the water layer in the element IX = IXCSRM(ISRM) of the connecting junction.

Also, for JRMCRB(ISRM) = 0 as the user-specified value of the integer control parameter for specifying the conditions of the bottom concentration of the radionuclide in the flow of stream or tributary ISRM into the bottom layer of the main flow channel, the computation stage of STREAM automatically neglects the part representing the radionuclide transport associated with the flow of stream or tributary

ISRM into the bottom layer of the main flow channel [Eq. (2.19)], by assuming the bottom concentration of the radionuclide in the flow of stream or tributary ISRM into the bottom layer of the main flow channel CRBSRM(ISRM,IPER) = CRB(IX) as the bottom concentration of the radionuclide in the bottom layer in the element IX = IXCSRM(ISRM) of the connecting junction.

Hence, although STREAM includes all the necessary capabilities for incorporating detailed information about the flow conditions and radionuclide concentration conditions of a stream or tributary into the main flow channel, based on extensive specified input data sets, it also includes provisions to allow the user to implement the RADONE computer code based on simplified flow conditions and radionuclide concentration conditions of a stream or tributary into the main flow channel; these provisions require only simple specified input data sets with a very limited number of data records.

The third part of the preparation stage of STREAM consists of the following operational step (Fig. 6.12a):

4. For the value of the integer control parameter IWDATA = 1, which is read in the MAIN program (Sect. 6.2) and passed through the labeled COMMON/PUTOUT/, STREAM writes as printed output (Sect. 8.10) all the specified input data for flow conditions and the radionuclide concentration conditions in all streams or tributaries ISRM = 1, ..., NSRM flowing into or out of the main flow channel (Sect. 4.7).

The fourth part of the preparation stage of STREAM also includes special features that enable the user to implement the RADONE computer code with minimal amount of effort in accurately simulating detailed flow conditions and radionuclide concentration conditions in an actual controlled river or tidal estuary, based on extensive specified input data for flow conditions and radionuclide concentration conditions in the streams or tributaries flowing into or out of the main flow channel. The structure and computational procedure of STREAM include special provisions for aligning the time periods of the specified input data for flow conditions and radionuclide concentration conditions in streams or tributaries flowing into or out of the main flow channel with the internally calculated time levels of the solution, according to the general computational algorithm of the RADONE computer code. Hence, if the user already has extensive sets of specified input data for flow conditions and radionuclide concentration conditions in the streams or tributaries flowing into or out of the main flow channel for a long overall period (e.g., one week, one month, or one year), with large numbers of specified time periods (Sect. 4.7) for representing the short-term variations (e.g., 1 h, 1 d, or 1 week), the computer simulations with the RADONE computer code can be started at any time within the overall period of the available data, without requiring any modification of the extensive sets of specified input data. The internal computational algorithm of the preparation stage of STREAM automatically aligns the specified initial time (Sect. 6.4) with the appropriate specified time period of the specified input data for flow conditions and radionuclide concentration conditions in the streams or tributaries flowing into or out of the main flow channel. The detailed discussion of the special computational procedure for aligning the time periods of the specified input data for the flow conditions associated with streams or tributaries flowing into or out of the main flow channel with the internally calculated time level of the solution is presented in the users manual of the ESTONE computer code [Eraslan (1983)], which includes a similar modular subroutine STREAM for specifying the transport conditions associated with streams or tributaries flowing into or out of the main flow channel of a controlled river or a tidal estuary. Therefore, the discussion of the fourth part of the preparation stage of STREAM will be presented in a summary form in this report, in order to avoid extensive repetition of the same procedure that is common to the two computer codes of the UTA project [Eraslan et al. (1976), Eraslan and Witten (1984)]. Hence, in summary, the fourth part of the preparation stage of STREAM initiates and completes the necessary procedure for determining the appropriate specified time periods and specified input data for flow conditions and radionuclide concentration conditions that correspond to the specified initial time (Sect. 6.4), according to the following operational steps (Fig. 6.12a):

5. For the specified initial time T, which is read in the modular subroutine INITAL (Sect. 6.4) and passed through the labeled COMMON/CONTRL/, STREAM determines, for all streams or tributaries ISRM = 1, ..., NSRM, the appropriate specified time period for the flow conditions and radionuclide concentrations condition of each stream or tributary ISRM into or out of the main flow channel TRMPER(ISRM,IPER), which includes the specified initial time T (Sect. 4.7).
6. STREAM determines the flow conditions and radionuclide concentration conditions in all the streams or tributaries ISRM = 1, ..., NSRM flowing into or out of the main flow channel, at the specified initial time T (Sect. 4.7).

At the end of the preparation stage, STREAM completes all the necessary initialization procedures that would be required in the subsequent computation stage of the subroutine; then, it returns to the MAIN program.

6.12.2 Computation Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of the RADONE computer code, STREAM is called by the modular subroutine SOLVER at every intermediate time level of the numerical integration (solution) of the governing system of discrete-element equations of the mathematical transport model (Sect. 5).

The first part of the computation stage of STREAM determines the appropriate time period and the specified input data for the flow conditions and radionuclide concentration conditions in the streams or tributaries flowing into or out of the main flow channel that correspond to the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, according to the following operational steps (Fig. 6.12b):

1. Based on the value of the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, STREAM determines, for all the streams or tributaries ISRM = 1, ..., NSRM, the appropriate specified time period of the specified input data for flow conditions and radionuclide concentration conditions in each stream or tributary ISRM flowing into or out of the main flow channel TRMPER(ISRM,IPER). If the intermediate time level T extends beyond the specified time corresponding to the end of the last input record for the specified time period of the specified flow conditions of stream or tributary TRMPER(ISRM,NMXPER), NMXPER = NRMPER(ISRM), STREAM automatically retains the last specified time period TRMPER(ISRM,NMXPER); and it determines flow conditions and radionuclide concentration conditions of stream or tributary ISRM based on specified input data for the last specified time period TRMPER(ISRM,NMXPER).
2. STREAM determines the flow conditions and radionuclide concentration conditions in all streams or tributaries ISRM = 1, ..., NSRM flowing into or out of the main flow channel, at the intermediate time level T (Sect. 4.7).

The second part of the computation stage of STREAM completes the sixth step of the successive updating scheme [Eqs. (5.28a)-(5.28e)] used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer

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code by calculating the terms representing contributions of the transport associated with all stream or tributary flows, ISRM = 1, ..., NSRM, into or out of the main flow channels to the right-hand-side solution functions for the solutions of the principal solution variables in each element and half-element that contains the junction of a stream or tributary according to the following operational steps (Figs. 6.12b and 6.12c):

3. Based on values, already calculated in the modular subroutine REGION, for the detailed geometric properties of the cross sections IC = 1, ..., NC, which are passed to the subroutine through the labeled COMMON/GEOEST/, STREAM calculates, in each element that contains the junction of a stream or tributary IXCSRM(ISRM), all the required linearly interpolated values for the detailed geometric properties of the cross sections (Sect. 3.3.1) at three locations in the element. These locations are (a) in the upstream half-element IMXSRM = 2*IXCSRM(ISRM) − 1, (b) in the element IXRSRM = IXCSRM(ISRM), and (c) in the downstream half-element IPXSRM = 2*IXCSRM(ISRM).
4. STREAM calculates, in each element that contains the junction of a stream or tributary IXCSRM(ISRM), at each intermediate time level T, the part representing the water mass transport associated with the flow of stream or tributary ISRM into or out of the main flow channel [Eq. (5.9)] as the additional term to the value of the right-hand-side solution function (slope) FNCHSR(IXRSRM), which is stored in the labeled COMMON/HSRSOL/, for the solution of the water surface elevation HSR(IXRSRM) in the element IXRSRM = IXCSRM(ISRM) [Eq. (5.28a)].
5. STREAM calculates, at each intermediate time level T, the velocities (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with the flow of stream or tributary ISRM in the upstream half-element IMXSRM = 2*IXCSRM(ISRM) − 1 and in the downstream half-element IPXSRM = 2*IXCSRM(ISRM) of the element that contains the junction of the stream or tributary IXCSRM(ISRM), according to the generalized, nonspatial upwind-differencing interpolation formulas associated with specified flow transport conditions (Sect. 3.3.3). For stream or tributary ISRM flowing out of the main flow channel (i.e., GRMIII ≤ 0), the computational algorithm of STREAM calculates

    a. the velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) VLXMRM associated with the flow of stream or tributary ISRM in the upstream half-element IMXSRM, at the intermediate time level T, based on the channel flow rate (along the curvilinear longitudinal *x*-axis of the main flow channel) GFXIMX and the cross-sectional area ARXIMX in the upstream half-element [Eq. (3.18b)] and

    b. the velocity VLXPRM associated with the flow of stream or tributary ISRM in the downstream half-element IPXSRM, at the intermediate time level T, based on channel flow rate GFXIPX and the cross-sectional area ARXIPX in the downstream half-element [Eq. (3.18b)].

    For stream (or tributary) ISRM flowing into the main flow channel (i.e., GRMIII > 0), the computational algorithm of STREAM directly assigns [Eq. (3.18a)]

    a. the velocity associated with the flow of stream or tributary ISRM in the upstream half-element IMXSRM = 2*IXCSRM(ISRM) − 1, at the intermediate time level T, VLXMRM = VLXTFL(ISRM) = VLXSRM(ISRM,IPER) as the specified input data for the specified time period TRMPER(ISRM,IPER), for the velocity of stream or tributary ISRM flowing into the main stream flow channel [Eq. (4.69)] and

    b. the velocity associated with the flow of stream or tributary ISRM in the downstream half-element IPXSRM = 2*IXCSRM(ISRM), at the intermediate time level T, VLXPRM =

VLXTFL(ISRM) = VLXSRM(ISRM,IPER) as the specified input data for the specified time period TRMPER(ISRM,IPER) for the velocity of stream or tributary ISRM flowing into the main flow channel [Eq. (4.69)].

6. STREAM calculates, for each element that contains the junction of a stream or tributary IXCSRM(ISRM), at each intermediate time level T, the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with the flow of stream or tributary ISRM into or out of the main flow channel [Eq. (5.15)] as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IMXSRM), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IMXSRM) in the upstream half-element IMXSRM = 2*IXCSRM(ISRM) − 1 [Eq. (5.28b)].
7. STREAM calculates, for each element that contains the junction of a stream or tributary IXCSRM(ISRM), at each intermediate time level T, the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with the flow of stream or tributary ISRM into or out of the main flow channel [Eq. (5.21)] as the additional term to the value of the right-hand-side solution junction (slope) FNCGFX(IPXSRM), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IPXSRM) in the downstream half-element IPXSRM = 2*IXCSRM(ISRM) [Eq. (5.28c)].
8. For a stream or tributary ISRM flowing out of the main flow channel, GRMIII < 0, STREAM completely omits the calculations of the parts representing

   a. the radionuclide transport effect associated with the flow of stream or tributary ISRM out of the water layer of the main flow channel [Eqs. (2.10) and (5.28d)] and
   b. the radionuclide transport effect associated with the flow of stream or tributary ISRM out of the bottom layer of the main flow channel [Eqs. (2.19) and (5.28e)],

   according to

   a. the intensive form of the discrete-element formulations of the parts representing the radionuclide transport in (1) the discrete-element equation for water concentration of the radionuclide in the water layer [Eq. (2.4)] and (2) the discrete-element equation for bottom concentration of the radionuclide in the bottom layer [Eq. (2.16)] and
   b. the generalized, nonspatial, upwind-differencing interpolation forms of the specified transport for (1) water concentration of the radionuclide in the water layer [Eqs. (3.19a) and (3.19b)] and (2) the bottom concentration of the radionuclide in the bottom layer [Eqs. (3.20a) and (3.20b)], associated with the stream or tributary flow out of the main flow channel GRMIII < 0.

9. For a stream or tributary ISRM flowing into the main flow channel, GRMIII > 0, depending on the specified values of the input data for the temporally constant integer control parameters, STREAM again completely omits the calculations of the parts representing

   a. the radionuclide transport effect associated with the flow of stream or tributary ISRM into the water layer of the main flow channel [Eqs. (2.10) and (5.28d)], for the specified value of the integer control parameter JRMCRW(ISRM) = 0 and
   b. the radionuclide transport effect associated with the flow of stream or tributary ISRM into the bottom layer of the main flow channel [Eqs. (2.19) and (5.28e)].

Hence, only for the combination of the two conditions, corresponding to

a. stream or tributary ISRM flowing into the main flow channel, GRMIII > 0 and
b. JRMCRW(ISRM) = 1 (or > 0) as the user-specified value of the integer control parameter indicating that the water concentration of the radionuclide in the water of stream or tributary CRWTFL(ISRM) = CRWSRM(ISRM,IPER) as the specified input data for the water concentration of the flow of stream or tributary ISRM into the water layer of the main flow channel, for the specified time period TRMPER(ISRM,IPER) [Eq. (4.70)].

10. STREAM calculates, for the element that contains the junction of the stream or tributary IXCSRM(ISRM), at each intermediate time level T, the part representing the radionuclide transport associated with the flow of stream or tributary ISRM into the water layer of the main flow channel [Eq. (5.28d)] as the additional term to the value of the right-hand-side solution function (slope) FNCCRW(IXRSRM), which is stored in the labeled COMMON/CRWSOL/, for the solution of water concentration of the radionuclide in the water layer CRW(IX) in the element IXRSRM = IXCSRM(ISRM) [Eq. (5.4a)].

    Similarly, only for the combination of two conditions, corresponding to

    a. stream or tributary ISRM flowing into the main flow channel, GRMIII > 0 and
    b. JRMCRB(ISRM) = 1 (or > 0) as the user-specified value of the integer control parameter indicating that the bottom concentration of the radionuclide in the water of stream or tributary CRBTFL(ISRM) = CRBSRM(ISRM,IPER) as the specified input data for the bottom concentration of the flow of stream or tributary ISRM into the bottom layer of the main flow channel, for the specified time period TRMPER(ISRM,IPER) [Eq. (4.71)].

11. Based on specified depth of the bottom layer DHBBED, which is passed to the subroutine through the labeled COMMON/BEDCON/, and the assumed self-similar vertical and lateral distribution of the channel flow velocity over the cross section of the main flow channel [Eqs. (3.31a), (3.31b), and (3.32)], STREAM calculates the GRBIII as the part of the flow rate of the stream or tributary ISRM flowing into the bottom layer of the main flow channel.
12. STREAM calculates, for the element that contains the junction of the stream or tributary IXCSRM(ISRM), at each intermediate time level T, the part representing the radionuclide transport associated with the flow of stream or tributary ISRM into the bottom layer of the main flow channel [Eq. (5.28e)] as the additional term to the value of the right-hand-side solution function (slope) FNCCRB(IXRSRM), which is stored in the labeled COMMON/CRBSOL/, for the solution of the bottom concentration of the radionuclide in the bottom layer CRB(IX) in the element IXRSRM = IXCSRM(ISRM) [Eq. (5.5a)].

At the end of the computation stage, STREAM completes the calculations, at the intermediate time level T, for all terms representing the transport associated with the flow of all streams or tributaries ISRM = 1, ..., NSRM flowing into or out of the main flow channel, which collectively represent the sixth step in the computational construction of all the right-hand-side solution functions for the solutions of all principal solution variables in all elements and half-elements, according to the successive updating scheme, used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code; then, it returns to the modular subroutine SOLVER.

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The structure and computational procedure of STREAM of the advanced development program version of the RADONE computer code were specifically designed to enable the user to understand, without undue difficulty, (1) the requirements for the preparation of specified input data and (2) the computational algorithms associated with the formulations of temporally varying flow conditions and radionuclide concentration conditions of streams or tributaries flowing into or out of the main flow channel, which are generally encountered in applications of the computer code for the assessment of the radiological impact on the receiving water body that would result from accidental radiological release scenarios which can contaminate the streams and/or tributaries of a river or an estuary. Hence, the structure of STREAM reads and stores all the specified sets of input data for all streams or tributaries and for all the specified time periods in the structurally separated part associated with the preparation stage of the subroutine. In certain applications of the RADONE computer code for continuous, long-term, and accurate simulations of flow conditions and radionuclide concentration conditions in a controlled river or a tidal estuary during a relatively long period (e.g., six months), based on specified sets of input data with relatively high temporal resolution (e.g., 1 d or 1 h) for a large number of streams or tributaries flowing into or out of the main flow channel, STREAM could require substantial storage. Particularly in computer systems operating in an interactive, time-sharing mode, this excessive storage requirement of STREAM could become a problem because excessive core storage allocations to the program could also reduce the overall computational speed of the complete system. This problem can (and should) be avoided by considering successive runs with the RADONE computer code for shorter simulation periods (e.g., one month) and only with the parts of the specified input data sets required for each particular simulation period. Because the RADONE computer code automatically includes the necessary restart capability through the modular subroutine OUTPUT (Sect. 6.15) and the modular subroutine INITAL (Sects. 6.4 and 7.4), the user can (and should) separate the specified sets of the input data for a relatively long simulation period (e.g., six months) into partial specified sets of input data for relatively shorter simulation periods (e.g., one month) and apply the code successively by restarting the computations for each successive, relatively shorter period.

The "production program" version of the RADONE computer code can completely eliminate the storage requirement for the specified sets of input data for each specified time period for the flow conditions and radionuclide concentration conditions associated with a stream and/or tributary flowing into or out of the main flow channel of a river or an estuary by combining the preparation stage and the computation stage into a single computation stage in the modular subroutine STREAM.

6.13 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE PLANTS

The modular subroutine PLANTS represents the computational algorithm for formulating the contribution of transport associated with plant operational conditions along the main flow channel, which control intake and discharge flows into and/or out of the main flow channel, to the solution of flow conditions in the NX number of elements and 2*NX number of half-elements, according to the one-dimensional formulation of the discrete-element model of the RADONE computer code (Sects. 2, 4.8, and 5.2). PLANTS is the seventh of the eight major modular subroutines that are called by the computational procedure of the modular subroutine SOLVER, according to the sequential computational method [Eqs. (5.29a)–(5.29e)], based on the successive updating scheme for the solution of 5*NX number of right-hand-side solution functions, consisting of (1) $[F_{PLT}(\overline{H})]_i$ in all N elements [Eqs. (5.10) and (5.29a)], (2) $[F_{PLT}(\overline{G}_x)]_{i-1/4}$ in all N upstream half-elements [Eqs. (5.16) and (5.29b)], (3) $[F_{PLT}(\overline{G}_x)]_{i+1/4}$ in all N downstream half-elements [Eqs. (5.22) and (5.29c)], (4) $[F_{PLT}(\overline{C}_{rw})]_i$ in all N elements [Eqs. (2.11) and (5.29d)], and (5) $[F_{PLT}(\overline{C}_{rb})]_i$ in all N elements [Eqs. (2.20) and (5.29b)].

PLANTS represents the computational procedure associated with formulation of the effects of the detailed operational conditions of plants located along the curvilinear longitudinal x-axis of the main flow channel of a river or an estuary. The computational algorithm of PLANTS is specifically designed to incorporate any number of plants, with wide ranges of operational conditions (Sect. 4.8). The generalized formulations of specified plant operational conditions can accurately represent the flow conditions and radionuclide concentration conditions associated with any type of intake and discharge conditions, including (1) power plants, (2) pump-storage stations, (3) commercial and public water treatment systems, and (4) large-scale industrial facilities.

The structure and computational procedure of PLANTS (Figs. 6.13a–6.13c) consist of two operational stages, the preparation stage and the computation stage, which are initiated and completed, depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.13.1 Preparation Stage

PLANTS is first called from the MAIN program with the value of the integer control parameter KRUN = 0 (Fig. 6.12), which is passed to the subroutine through the labeled COMMON/CONTRL/.

PLANTS first reads (Fig. 6.13a) NPLT as the specified input data (Sect. 7.12) for the number of plants along the curvilinear longitudinal x-axis of the main flow channel. The specified number of plants along the main flow channel NPLT is stored in the labeled COMMON/CONTRL/, and it is passed to the modular subroutine SOLVER (Sect. 6.5).

For the specified input data for NPLT = 0, which corresponds to the case without any operating plants along the main flow channel of the river or estuary, PLANTS returns to the MAIN program without any operational step (Fig. 6.13a) because it does not need to read any additional specified input data.

For the specified input data for NPLT > 0, which corresponds to the case with one or more plants operating along the main flow channel of the river or estuary, PLANTS initiates the first part of the preparation stage for reading the specified input data for the locations and control conditions at the intakes and discharges of all plants IPLT = 1, ..., NPLT along the main flow channel, according to the following operational steps (Fig. 6.13a). The detailed definitions of most of this set of specified input data are presented in Sects. 4.8 and 7.12; hence, the following discussions of the operational steps of the preparation stage of PLANTS will only state the FORTRAN variable of each coefficient or parameter and its corresponding mathematical variable and will only indicate the sections that contain its detailed definition.

1. PLANTS reads the specified input data (Sect. 7.12) for
    a. [PLNAME(IPLT,ID), ID = 1,40] as the specified name (with a maximum of 40 letters) of the plant along the main flow channel and
    b. NPLPER(IPLT) as the specified number of time periods for formulating the temporal variations (or temporally uniform conditions) of the operational conditions of plant IPLT along the main flow channel.

2. PLANTS reads the specified input data (Sect. 7.12) for the geometric and control conditions associated with the intake of the plant. This data set consists of
    a. IXPINT(IPLT) as $i_{int,m}$ [Eq. (4.72)],
    b. DHBINT(IPLT) as $\overline{D}_{int,m}$ [Eqs. (4.74) and (4.92)],

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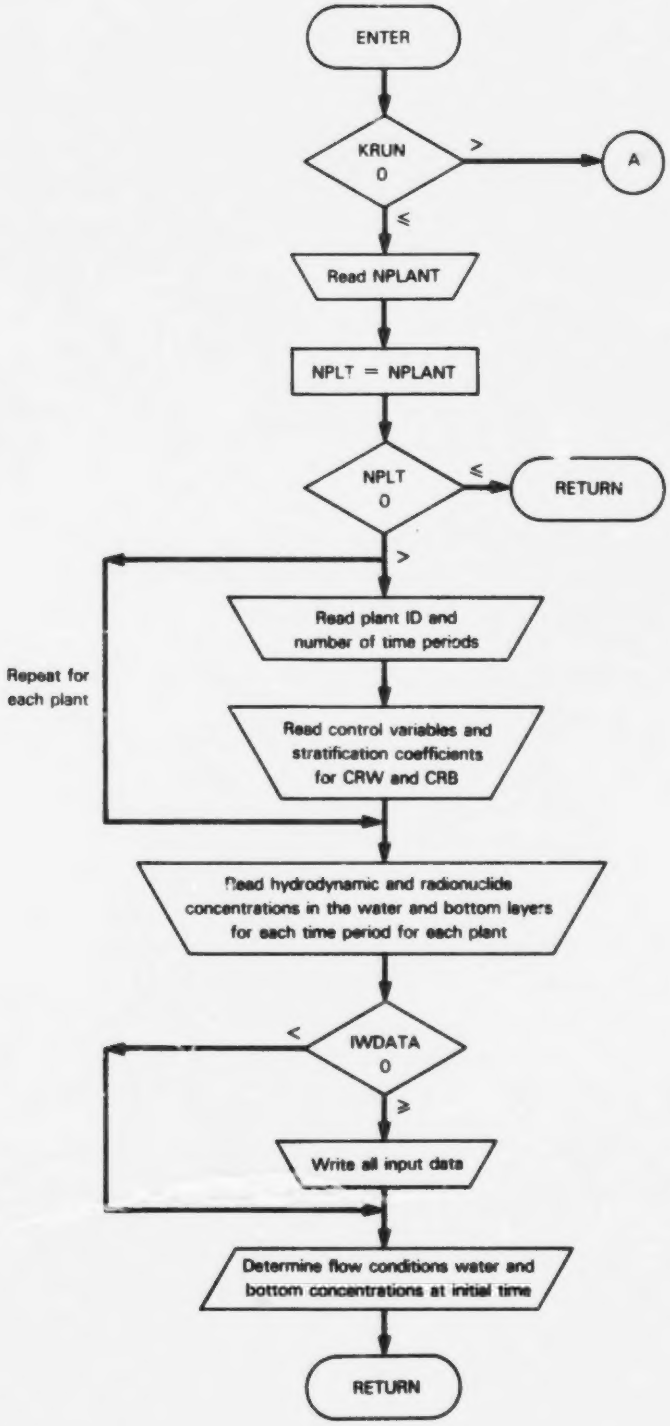
ENTER
KRUN
0
>
A
≤
Read NPLANT
NPLT = NPLANT
NPLT
0
≤
RETURN
>
Read plant ID and number of time periods
Repeat for each plant
Read control variables and stratification coefficients for CRW and CRB
Read hydrodynamic and radionuclide concentrations in the water and bottom layers for each time period for each plant
IWDATA
0
<
≥
Write all input data
Determine flow conditions water and bottom concentrations at initial time
RETURN

Fig. 6.13a. Abbreviated flowchart of the structure and computational procedure of the modular subroutine PLANTS of the RADONE computer code.

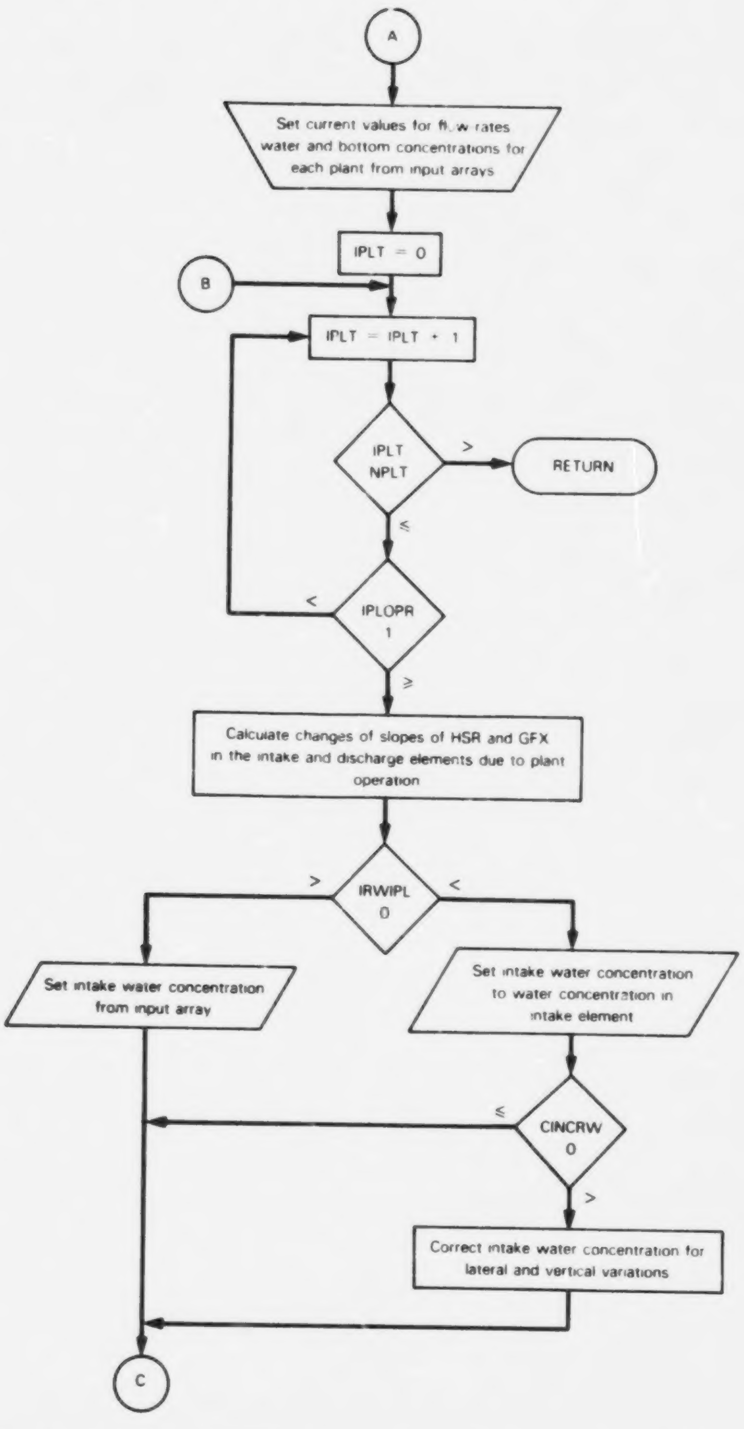
A
Set current values for flow rates water and bottom concentrations for each plant from input arrays
IPLT = 0
B
IPLT = IPLT + 1
IPLT NPLT
>
RETURN
≤
IPLOPR 1
<
≥
Calculate changes of slopes of HSR and GFX in the intake and discharge elements due to plant operation
IRWIPL 0
>
<
Set intake water concentration from input array
Set intake water concentration to water concentration in intake element
CINCRW 0
≤
>
Correct intake water concentration for lateral and vertical variations
C

Fig. 6.13b. Abbreviated flowchart of the structure and computational procedure of the modular subroutine PLANTS of the RADONE computer code (continued).

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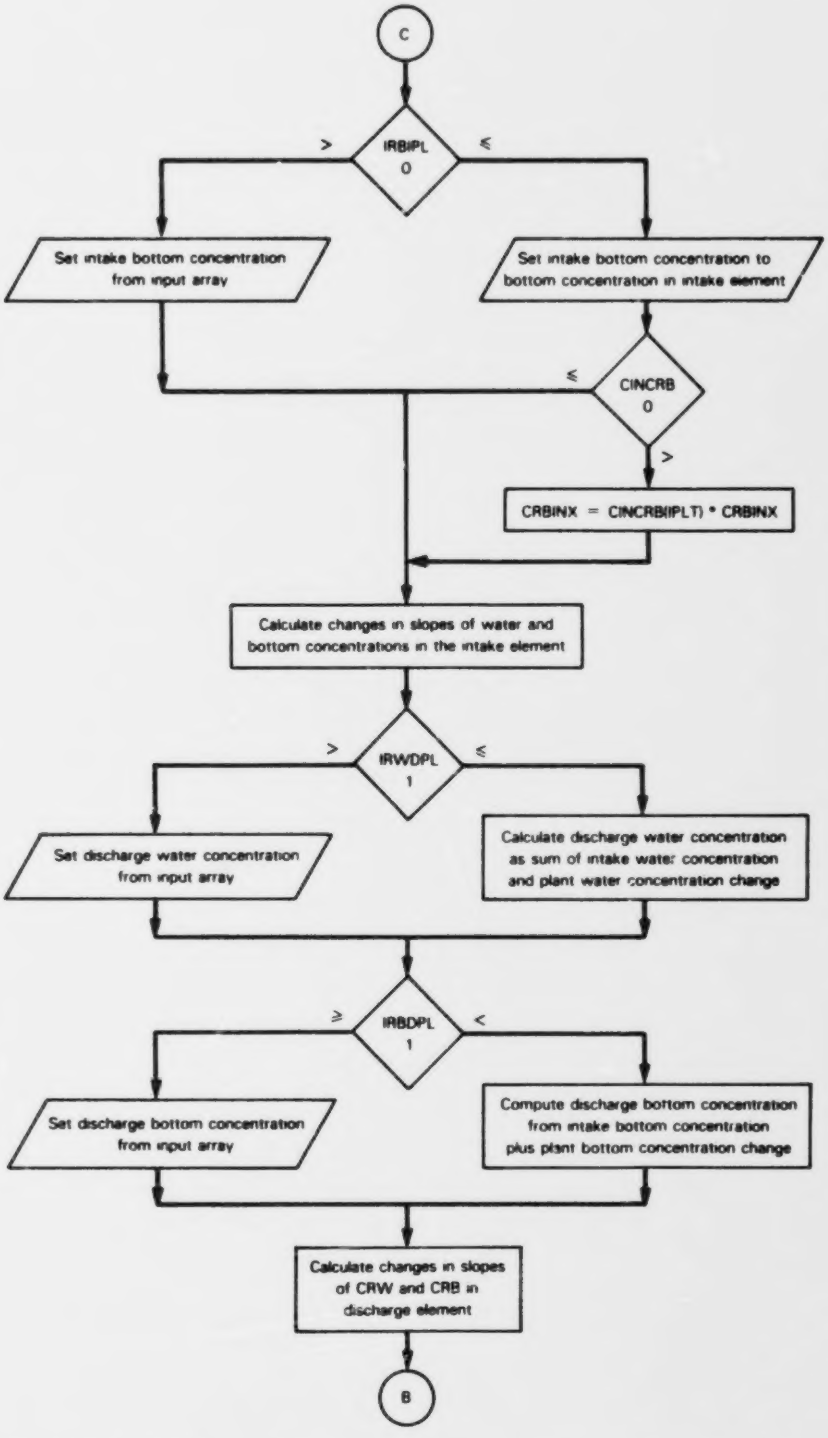
C
IRBIPL 0
>
≤
Set intake bottom concentration from input array
Set intake bottom concentration to bottom concentration in intake element
CINCRB 0
≤
>
CRBINX = CINCRB(IPLT) * CRBINX
Calculate changes in slopes of water and bottom concentrations in the intake element
IRWDPL 1
>
≤
Set discharge water concentration from input array
Calculate discharge water concentration as sum of intake water concentration and plant water concentration change
IRBDPL 1
≥
<
Set discharge bottom concentration from input array
Compute discharge bottom concentration from intake bottom concentration plus plant bottom concentration change
Calculate changes in slopes of CRW and CRB in discharge element
B

Fig. 6.13c. Abbreviated flowchart of the structure and computational procedure of the modular subroutine PLANTS of the RADONE computer code (continued).

   c. DHBBOT(IPLT) as $\overline{D}_{bot,int,m}$ [Eqs. (4.75) and (4.92)],
   d. RGFINT(IPLT) as $R_{wl,int,m}$ [Eqs. (4.76), (4.87), and (4.88)],
   e. CINCRW(IPLT) as $k_{rw,int,m}$ [Eqs. (4.77), (4.93a), and (4.93b)], and
   f. CINCRB(IPLT) as $k_{rb,int,m}$ [Eqs. (4.78) and (4.97)].

3. PLANTS reads the specified input data (Sect. 7.12) for the geometric and control conditions associated with the discharge of the plant. This data set consists of

   a. IXPDIS(IPLT) as $i_{dis,m}$ [Eq. (4.73)],
   b. RGFDIS(IPLT) as $R_{wl,dis,m}$ [Eqs. (4.79), (4.101), and (4.102)],
   c. CDICRW(IPLT) as $k_{rw,dis,m}$ [Eqs. (4.80), (4.105), and (4.107)], and
   d. CDICRB(IPLT) as $k_{rb,dis,m}$ [Eqs. (4.81), (4.110), and (4.112)].

The second part of the preparation stage of PLANTS reads, for all the power plants IPLT = 1, ..., NPLT, the specified input data (Sect. 7.12) for temporal variations of the operational conditions and radionuclide concentration conditions of each plant along the main flow channel according to the following operational steps (Fig. 6.13a). Again, the definitions of most of this set of specified input data are presented in Sects. 4.8 and 7.12; hence, the following discussions of the operational steps of the preparation stage of PLANTS will only state the FORTRAN variable of each operational condition and its corresponding mathematical variable and will only indicate the sections that contain its detailed definition.

4. PLANTS reads, for each plant IPLT, the specified set of input data, as IPER = 1, ..., NPER = NPLPER(IPLT) list of records (Sect. 7.12), for the durations of the specified time periods (Sect. 4.8) and the detailed specified information about the operational conditions associated with the intake flow of plant IPLT into or out of the main flow channel, during the specified time periods. This data set (Sect. 7.12) consists of

   a. IPLOPR(IPLT,IPER) as $J_{opr,m,p}$ [Eq. (4.82)],
   b. TPLPER(IPLT,IPER) as $\Delta t_{plt,m,p}$ [Eqs. (4.82)–(4.86), (4.89), (4.90), (4.95), (4.96), (4.99), (4.100), (4.103), (4.104), (4.106), (4.108), (4.109), and (4.111)],
   c. GFLINT(IPLT,IPER) as $\overline{G}_{int,m,p}$ [Eq. (4.83)],
   d. VLXINT(IPLT,IPER) as $\overline{V}_{x,int,m,p}$ [Eq. (4.84)],
   e. JINCRW(IPLT,IPER) as $J_{rw,int,m,p}$ [Eq. (4.89)],
   f. CRWINT(IPLT,IPER) as $C_{rw,int,m,p}$ [Eq. (4.90)],
   g. JINCRB(IPL,IPER) as $J_{rb,int,m,p}$ [Eq. (4.95)], and
   h. CRBINT(IPLT,IPER) as $C_{rb,int,m,p}$ [Eq. (4.96)].

5. PLANTS reads, for each plant IPLT, the specified set of input data, as IPER = 1, ..., NPER = NPLPER(IPLT) list of additional records (Sect. 7.12), the detailed specified information about the operational conditions associated with the discharge flow of plant IPLT into the main flow channel, during the specified time periods. This data set (Sect. 7.12) consists of

   a. GFLDIS(IPLT,IPER) as $\overline{G}_{dis,m,p}$ [Eq. (4.99)],
   b. VLXDIS(IPLT,IPER) as $V_{x,dis,m,p}$ [Eq. (4.100)],
   c. JDICRW(IPLT,IPER) as $J_{rw,dis,m,p}$ [Eq. (4.103)],
   d. CRWDIS(IPLT,IPER) as $C_{rw,dis,m,p}$ [Eqs. (4.104) and (4.106)],
   e. JDICRB(IPLT,IPE) as $J_{rb,dis,m,p}$ [Eq. (4.108)], and
   f. CRBDIS(IPLT,IPER) as $C_{rb,dis,m,p}$ [Eqs. (4.109) and (4.111)].

It is important to point out that extensive specified input data sets for operational conditions of the power plants are required only for long-term and accurate representations of the temporal variations of the principal solution variables associated with intake and discharge flows of power plants into or out of the main flow channel for obtaining long-term and accurate computer simulations, by the application of the RADONE computer code, for flow conditions and radionuclide concentration conditions in a controlled river or a tidal estuary. For temporally uniform operational conditions of a plant IPLT, only a single-record specified input data set, with IPER = NPLPER(IPLT) = 1, would be sufficient to represent the temporally uniform conditions for the principal solution variables associated with intake and discharge flows of the power plant. Hence, although PLANTS includes all the necessary capabilities for incorporating detailed information about operational conditions of plants along the main flow channel, based on extensive specified input data sets, it also includes provisions to allow the user to implement the RADONE computer code based on simplified operational conditions of a plant along the main flow channel, which require only simple specified input data sets with a very limited number of data records.

The third part of the preparation stage of PLANTS consists of the following operational step (Fig. 6.13a):

6. For the value of the integer control parameter IWDATA = 1, which is read in the MAIN program (Sect. 6.2) and passed through the labeled COMMON/PUTOUT/, PLANTS writes as printed output (Sect. 8.9) all specified input data sets for the operational conditions of all plants IPLT = 1, ..., NPLT along the main flow channel of a river or an estuary (Sect. 4.8).

The fourth part of the preparation stage of PLANTS also includes special features that enable the user to implement the RADONE computer code with minimal effort in simulating accurately the detailed flow conditions and radionuclide concentration conditions in an actual controlled river or a tidal estuary, based on extensive specified input data for plant operational conditions that control the conditions of intakes and discharges into or out of the main flow channel. The structure and computational procedure of PLANTS include special provisions for aligning the time periods of the specified input data for the operational conditions of plants along the main flow channel with the internally calculated time levels of the solution, according to the general computational algorithm of the RADONE computer code. Hence, if the user already has extensive sets of specified input data for the operational conditions of plants along the main flow channel for a long overall period (e.g., one week, one month, or one year) with a large number of specified time periods (Sect. 4.8) for representing the short-term variations (e.g., 1 h, 1 d, or 1 week), the computer simulations with the RADONE computer code can be started at any time within the overall period of the available data, without requiring any modification of the extensive sets of specified input data. The internal computational algorithm of the preparation stage of PLANTS automatically aligns the specified initial time (Sect. 6.4) with the appropriate specified time period of the specified input data for the operational conditions of plants along the main flow channel. The detailed discussion of the special computational procedure for aligning the time periods of the specified input data for the flow conditions associated with the intakes and discharges of plants operating along the main flow channel with internally calculated time of the solution is presented in the users manual of the ESTONE computer code [Eraslan (1983)] which includes a similar modular subroutine PLANTS for specifying the transport conditions associated with the plants operating along a river or an estuary. Therefore, the discussion of the fourth part of the preparation stage of PLANTS will be presented in a summary form in this report, in order to avoid extensive repetition of the procedure that is common to two computer codes of the UTA project [Eraslan et al. (1976), Eraslan and Witten (1984)]. Hence, in summary, the fourth part of the preparation stage of

PLANTS initiates and completes the necessary procedure for determining the appropriate specified time periods and specified input data for flow and radionuclide concentration conditions of the plants that correspond to the specified initial time (Sect. 6.4), according to the following operational steps (Fig. 6.13a):

7. For the specified initial time T, which is read in the modular subroutine INITAL (Sect. 6.4) and passed through the labeled COMMON/CONTRL/, PLANTS determines, for all plants, IPLT = 1, ..., NPLT, the appropriate specified time period of the specified input data for the operational conditions of each plant IPLT associated with the conditions of intake and discharge flows of plant IPLT into or out of the main flow channel TPLPER(IPLT,IPER), which includes the specified initial time T (Sect. 4.8).
8. PLANTS determines conditions associated with the intake and discharge flows of all plants, IPLT = 1, ..., NPLT, at the specified initial time T, by assigning
    a. intake flow rate of the plant GFLIPL(IPLT) = GFLINT(IPLT,IPER) [Eq. (4.83)],
    b. velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the intake flow of the plant VLXIPL(IPLT = VLXINT(IPLT,IPER) [Eq. (4.84)],
    c. integer control parameter associated with the water concentration of the radionuclide of the intake flow of the plant IRWIPL(IPLT) = JINCRW(IPLT,IPER) [Eq. (4.89)],
    d. water concentration of the radionuclide of the intake flow, withdrawn from the water layer, into the intake of the plant CRWIPL(IPLT = CRWINT(IPLT,IPER) [Eq. (4.90)],
    e. integer control parameter associated with the bottom concentration of the radionuclide of the intake flow of the plant IRBIPL(IPLT) = JINCRB(IPLT,IPER) [Eq. (4.95)],
    f. bottom concentration of the radionuclide of the intake flow withdrawn from the bottom layer into the intake of the plant CRBIPL(IPLT) = CRBINT(IPLT,IPER) [Eq. (4.96)],
    g. discharge flow rate of the plant GFLDPL(IPLT) = GFLDIS(IPLT,IPER) [Eq. (4.99)],
    h. velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the discharge flow of the plant VLXDPL(IPLT) = VLXDIS(IPLT,IPER) [Eq. (4.100)],
    i. integer control parameter associated with the water concentration of the radionuclide discharge flow of the plant IRWDPL(IPLT) = JDICRW(IPLT,IPER) [Eq. (4.103)],
    j. water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge of the plant CRWDPL(IPLT) = CRWDIS(IPLT,IPER) [Eqs. (4.104)–(4.107)],
    k. integer control parameter associated with the bottom concentration of the radionuclide of the discharge flow of the plant IRBDPL(IPLT) = JDICRB(IPLT,IPER) [Eq. (4.108)], and
    l. bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge of the plant CRBDPL(IPLT) = CRBDIS(IPLT,IPER) [Eqs. (4.108)–(4.112)].

At the end of the preparation stage, PLANTS completes all the necessary initialization procedures that would be required in the subsequent computation stage; then, it returns to the MAIN program.

6.13.2 Computation Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of the RADONE computer code, PLANTS is called by the modular subroutine SOLVER at every intermediate time level of the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5).

The first part of the computation stage of PLANTS determines the appropriate time period and the specified input data for the operational conditions of plants along the main flow channel that correspond to the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, according to the following operational steps (Fig. 6.13b):

1. Based on the value of the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, PLANTS determines, for all plants IPLT = 1, ..., NPLT, the appropriate specified time period of the specified input data for the operational conditions of each plant IPLT associated with the conditions of intake and discharge flows of plant IPLT into or out of the main flow channel TPLPER(IPLT,IPER). If the intermediate time level T extends beyond the specified time corresponding to the end of the last input record for the specified time period of the specified operational conditions of the plant TPLPER(IPLT,NMXPER), NMXPER = NPLPER(IPLT), PLANTS automatically retains the last specified time period TPLPER(IPLT,NMXPER); and it determines operational conditions of plant IPLT associated with the conditions of intake and discharge flows of plant IPLT into (or out of) the main flow channel based on specified input data for the last specified time period TPLPER(IPLT,NMXPER).
2. PLANTS determines for each plant, IPLT = 1, ..., NPLT, the flow conditions and the radionuclide concentration conditions associated with the specified operational conditions of the intake and discharge of each plant IPLT, at the intermediate time level T (Sect. 4.8), by assigning the values of the same set of variables (step 8 of the Preparation Stage, Sect. 6.13.1) to the corresponding set of specified input data for the variables during the specified time period TPLPER(IPLT,IPER) that includes the intermediate time level T.

The second part of the computation stage of PLANTS completes the seventh step of the successive updating scheme [Eqs. (5.29a)–(5.29e)] used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code by calculating the terms representing the contributions of the transport associated with the intake and discharge flows of all plants IPLT = 1, ..., NPLT, into or out of the main flow channel, to the right-hand-side solution functions for solutions of the principal solution variables in each element and half-element that contains the intake and/or discharge of a plant, according to the following operational steps (Figs. 6.13b):

3a. For the specified value of the integer control parameter IPLOPR(IPLT,IPER) = 0 (or < 1), which represents the user-specified option, for the specified time period TPLPER(IPLT,IPER), which indicates that plant IPLT is not operational during the specified time period TPLPER(IPLT,IPER), PLANTS omits all calculations for plant IPLT [Eq. (4.82)].

3b. For the specified value of the integer control parameter IPLOPR(IPLT,IPER) = 1 (or > 0), which represents the user-specified option, for the specified time period TPLPER(IPLT,IPER), which indicates that the plant is operational during the specified time period TPLPER(IPLT,IPER), PLANTS proceeds with necessary calculations for the plant IPLT [Eq. (4.82)].

4. Based on values, already calculated in the modular subroutine REGION, for the detailed geometric properties of the cross sections IC = 1, ..., NC, which are passed to the subroutine through the labeled COMMON/GEOEST/, PLANTS calculates, in each element that contains the intake IXPINT(IPLT) and/or the discharge IXPDIS(IPLT) of a plant IPLT, all the required linearly interpolated values for the geometric properties of the cross sections (Sect. 3.3.1) at three locations in the element. These locations are (a) in the upstream half-element IMXINT = 2*IXPINT(IPLT) − 1 and/or IMXDIS = 2*IXPDIS(IPLT) − 1, (b) in the element IXRINT = IXPINT(IPLT)

and/or IXRDIS = IXPDIS(IPLT), and (c) in the downstream half-element IPXINT = 2*IXPINT(IPLT) and/or IPXDIS = 2*IXPDIS(IPLT).

5. PLANTS calculates, in the element that contains the intake IXPINT(IPLT), at each intermediate time level T, the part representing water mass transport associated with the intake flow of plant IPLT into or out of the main flow channel [Eq. (5.10)] as the additional term to the value of the right-hand-side solution function (slope) FNCHSR(IXRINT), which is stored in the labeled COMMON/HSRSOL/, for the solution of water surface elevation HSR(IXRINT) in the intake element IXRINT = IXPINT(IPLT) [Eq. (5.29a)].
6. PLANTS calculates, in the element that contains the discharged IXPDIS(IPLT), at each intermediate time level T, the part representing water mass transport associated with the discharge flow of plant IPLT into the main flow channel [Eq. (5.10)] as the additional term to the value of the right-hand-side solution function (slope) FNCHSR(IXRINT), which is stored in the labeled COMMON/HSRSOL/, for the solution of water surface elevation HSR(IXRDIS) in the discharge element IXRDIS = IXPDIS(IPLT) [Eq. (5.29a)].
7. For the specified value of velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the intake flow of plant IPLT, at the intermediate time level T, VLXIPL(IPLT) = 0, which represents the user-specified option for indicating unknown velocity conditions for the intake flow of plant IPLT, PLANTS calculates, at the intermediate time level T, according to the generalized, nonspatial, upwind-differencing interpolation formulas associated with specified flow transport conditions (Sect. 3.3.3):

    a. VLXIMX as velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the intake flow of plant IPLT, from the upstream half-element IMXINT = 2*IXPINT(IPLT) − 1, based on channel flow rate (along the curvilinear longitudinal *x*-axis of the main flow channel) GFX(IMXINT) and the cross-sectional area ARXIMX in the upstream half-element IMXINT = 2*IXPINT(IPLT) − 1 [Eq. (3.7a)] and
    b. VLXIPX as velocity of the intake flow of plant IPLT from the downstream half-element IPXINT = 2*IXPINT(IPLT), based on channel flow rate GFX(IPXINT) and the cross-sectional area ARXIPX in the downstream half-element IPXINT = 2*IXPINT(IPLT) [Eq. (3.7c)].

8. For the preceding case of the user-specified option for indicating unknown velocity conditions for the flow of the intake of plant IPLT, PLANTS calculates, for the element that contains the intake IXPINT(IPLT), at each intermediate time level T, the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with the intake flow of plant IPLT into or out of the main flow channel [Eq. (5.16)] as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IMXINT), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IMXINT) in the upstream half-element IMXINT = 2*IXPINT(IPLT) − 1 [Eq. (5.29b)].
9. For the preceding case of the user-specified option for indicating unknown velocity conditions for the flow of the intake of plant IPLT, PLANTS calculates, for the element that contains the intake IXPINT(IPLT), at each intermediate time level T, the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with the intake flow of plant IPLT into or out of the main flow channel [Eq. (5.22)] as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IPXINT), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IPXINT) in the downstream half-element IPXINT = 2*IXPINT(IPLT) [Eq. (5.29c)].

10. For the specified value of velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the intake flow of plant IPLT, at the intermediate time level T, VLXIPL(IPLT) ≠ 0, which represents the user-specified option for indicating known velocity conditions for the intake flow of plant IPLT, PLANTS directly assigns

    a. velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the intake flow of plant IPLT in the upstream half-element IMXINT = 2*IXPINT(IPLT) − 1, at the intermediate time level T, VLXIMX = VLXIPL(IPLT) = VLXINT(IPLT,IPER) as the specified input data for velocity of the intake flow of plant IPLT into or out of the main flow channel, for the specified time period TPLPER(IPLT,IPER) [Eq. (4.84)] and
    b. velocity of the intake flow of plant IPLT from the downstream half-element IPXINT = 2*IXPINT(IPLT), at the intermediate time level T, VLXIPX = VLXIPL(IPLT) = VLXINT(IPLT,IPER) as the specified input data for velocity of the intake flow of plant IPLT into or out of the main flow channel, for the specified time period TPLPER(IPLT,IPER) [Eq. (4.84)].

11. For the preceding case of the user-specified option for known velocity conditions for the flow of the intake of plant IPLT, based on specified input data, PLANTS calculates, for the element that contains the intake IXPINT(IPLT), at each intermediate time level T, the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with the intake flow of plant IPLT into or out of the main flow channel [Eq. (5.16)] as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IMXINT), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IMXINT) in the upstream half-element IMXINT = 2*IXPINT(IPLT) − 1 [Eq. (5.29b)].
12. For the preceding case of the user-specified option for known velocity conditions for the flow of the intake of plant IPLT, based on specified input data, PLANTS calculates, for the element that contains the intake IXPINT(IPLT), at each intermediate time level T, the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with the intake flow of plant IPLT into or out of the main flow channel [Eq. (5.22)] as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IPXINT), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IPXINT) in the downstream half-element IPXINT = 2*IXPINT(IPLT) [Eq. (5.29c)].
13. For velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the discharge flow of plant IPLT, at the intermediate time level T, PLANTS directly assigns, according to the generalized, nonspatial upwind-differencing formulas associated with the specified flow transport condition (Sect. 3.3.3):

    a. velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the discharge flow of plant IPLT into the upstream half-element IMXDIS = 2*IXPDIS(IPLT − 1, at the intermediate time level T, VLXIMX = VLSDPL(IPLT) = VLXDIS(IPLT,IPER) as the specified input data for velocity of the discharge flow of plant IPLT into the main flow channel, for the specified time period TPLPER(IPLT,IPER) [Eq. (4.100)] and
    b. velocity of the discharge flow of plant IPLT into the downstream half-element IPXDIS = 2*IXPDIS(TPLT), at the intermediate time level T, VLXIPX = VLXDPL(IPLT) = VLXDIS(IPLT,IPER) as the specified input data for velocity of the discharge flow of plant IPLT into the main flow channel, for the specified time period TPLPER(IPLT,IPER) [Eq. (4.100)].

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14. PLANTS calculates, for the element that contains the discharge IXPDIS(IPLT), at each intermediate time level T, the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with the discharge flow of plant IPLT into the main flow channel [Eq. (5.16)] as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IMXDIS), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IMXDIS) in the upstream half-element IMXDIS = 2*IXPDIS(IPLT) − 1 [Eq. (5.29b)].

15. PLANTS calculates, for the element that contains the discharge IXPDIS(IPLT), at each intermediate time level T, the part representing momentum transport (along the curvilinear longitudinal *x*-axis of the main flow channel) associated with the discharge flow of plant IPLT into the main flow channel [Eq. (5.22)] as the additional term to the value of the right-hand-side solution function (slope) FNCGFX(IPXDIS), which is stored in the labeled COMMON/GFXSOL/, for the solution of channel flow rate GFX(IPXDIS) in the upstream half-element IPXDIS = 2*IXPDIS(IPLT) [Eq. (5.29c)].

16a. For the specified value of the integer control parameter IRWIPL(IPLT) = JINCRW(IPLT,IPER) = 0 (or < 1), which represents the user-specified option for calculating internally the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant IPLT, PLANTS calculates [Eqs. (4.93a) and (4.93b)] the upwind-differenced, transportive value of the water concentration of the radionuclide in the intake flow CRWINX, withdrawn from the water layer, into the intake structure of plant IPLT, based on the set of detailed, specified, and calculated conditions in the element IX = IXRINT = IXPINT(IPLT), which contains the intake of plant IPLT. This set of conditions consists of

    (1) CRWLOC as the vertically local water concentration of the radionuclide in the water layer [Eqs. (4.91) and (4.92)] at the specified depth of the intake DHBINT(IPLT) [Eqs. (4.74) and (4.92)] relative to the local specified depth of the bottom DHBBOT(IPLT) [Eqs. (4.75) and (4.92)] and

    (2) CINCRW(IPLT) as the specified constant coefficient for controlling the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant IPLT, representing the factor required for determining the effect of the vertical location of the intake structure relative to the water layer [Eqs. (4.77), (4.93a), and (4.93b)].

16b. For the specified value of the integer control parameter IRWIPL(IPLT) = JINCRW(IPLT,IPER) = 1 (or > 0), which represents the user-specified option for determining the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant IPLT, based on specified input data, PLANTS directly assigns the upwind-differenced, transportive value of the water concentration of the radionuclide in the intake flow CRWINX = CRWIPL(IPLT) = CRWINT(IPLT,IPER) as the specified input data for the water concentration of the radionuclide associated with the intake flow of plant IPLT, into or out of the main flow channel, for the specified time period TPLPER(IPLT,IPER) [Eqs. (4.90) and (4.94)].

17a. For the specified value of the integer control parameter IRBIPL(IPLT) = JINCRB(IPLT,IPE) = 0 (or < 1), which represents the user-specified option for calculating internally the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant IPLT, PLANTS calculates [Eq. (4.97)] the upwind-differenced, transportive value of the bottom concentration of the radionuclide in the intake flow CRBINX, withdrawn from the bottom layer, into the intake structure of plant IPLT based on the set specified and calculated conditions in the element IX = IXRINT = IXPINT(IPLT), which contains the intake of plant IPLT. This set of conditions consists of

(1) Bottom concentration of the radionuclide in the bottom layer CRBIII = CRB(IXRINT), which is passed to the subroutine through the labeled COMMON/CRBSOL/ (Sect. 6.5) and

(2) CINCRB(IPLT) as the specified constant coefficient for controlling the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant IPLT, representing the factor required for determining the effect of the vertical location of the intake structure relative to the bottom layer [Eqs. (4.78) and (4.97)].

17b. For the specified value of the integer control parameter IRBIPL(IPLT) = JINCRB(IPLT,IPER) = 1 (or > 0), which represents the user-specified option for determining the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant IPLT based on specified input data, PLANTS directly assigns the upwind-differenced, transportive value of the bottom concentration of the radionuclide in the intake flow CRBINX = CRBIPL(IPLT) = CRBINT(IPLT,IPER) as the specified input data for the bottom concentration of the radionuclide associated with the intake flow of plant IPLT, into or out of the main flow channel, for the specified time period TPLPER(IPLT,IPER) [Eqs. (4.96) and (4.98)].

18. PLANTS calculates, for the element that contains the intake IXPINT(IPLT), at each intermediate time level T, the part representing the radionuclide transport, associated with the intake flow of plant IPLT, withdrawn from or discharged into the water layer of the main flow channel [Eq. (5.29d)] as the additional term to the value of the right-hand-side solution function (slope) FNCCRW(IXRINT), which is stored in the labeled COMMON/CRWSOL/, for the solution of the water concentration of the radionuclide in the water layer CRW(IX) in the element IXRINT = IXPINT(IPLT) [Eq. (5.4a)].

19. PLANTS calculates, for the element that contains the intake IXPINT(IPLT), at each intermediate time level T, the part representing the radionuclide transport, associated with the intake flow of plant IPLT, withdrawn from or discharged into the bottom layer of the main flow channel [Eq. (5.29e)] as the additional term to the value of the right-hand-side solution function (slope) FNCCRB(IXRINT), which is stored in the labeled COMMON/CRBSOL/, for the solution of the bottom concentration of the radionuclide in the bottom layer CRB(IX) in the element IXRINT = IXPINT(IPLT) [Eq. (5.5a)].

20a. For the specified value of the integer control parameter IRWDPL(IPLT) = JDICRW(IPLT,IPER) = 0 (or < 1), which represents the user-specified option for calculating the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant IPLT, based on the radionuclide concentration rise in the plant IPLT, PLANTS calculates [Eqs. (4.104) and (4.105)] the transportive value of the water concentration of the radionuclide in the discharge flow CRWDIX, discharged into the water layer, from the discharge structure of plant IPLT, based on the set of specified and already calculated conditions. This set of conditions consists of

(1) CRWINX as the already calculated water concentration of the radionuclide in the intake flow of plant IPLT [Eqs. (4.89)–(4.94); step 16a or 16b],

(2) CRWDPL(IPLT) = CRWDIS(IPLT,IPER) as the specified input data for the radionuclide concentration rise, which represents the additional radionuclide release into the circulating water, discharged into the water layer, during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.104) and (4.105)], and

(3) CDICRW(IPLT) as the specified constant coefficient for controlling the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant IPLT, representing the factor required for approximately considering the effects of the design and structural features of the discharge of plant IPLT [Eqs. (4.80) and (4.105)].

20b. For the specified value of the integer control parameter IRWIPL(IPLT) = JDICRW(IPLT,IPER) = 1 (or > 0), which represents the user-specified option for determining the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant IPLT, based on specified input data, PLANTS directly assigns the transportive value of the water concentration of the radionuclide in the discharge flow CRWDIX = CRWDPL(IPLT) = CRWDIS(IPLT,IPER) as the specified input data for the water concentration of the radionuclide associated with the discharge flow of plant IPLT, into the main flow channel, for the specified time period TPLPER(IPLT,IPER) [Eq. (4.106)].

21a. For the specified value of the integer control parameter IRBDPL(IPLT) = JDICRB(IPLT,IPER) = 0 (or < 1), which represents the user-specified option for calculating the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant IPLT, based on the radionuclide concentration rise in the plant IPLT, PLANTS calculates [Eqs. (4.109) and (4.110)] the transportive value of the bottom concentration of the radionuclide in the discharge flow CRBDIX, discharged into the bottom layer, from the discharge structure of plant IPLT, based on the set of specified and already calculated conditions. This set of conditions consists of

(1) CRWDIX as the already calculated bottom concentration of the radionuclide in the intake flow of plant IPLT [Eqs. (4.95)–(4.98); steps 17a and 17b],

(2) CRBDPL(IPLT) = CRBDIS(IPLT,IPER) as the specified input data for the radionuclide concentration rise, which represents the additional radionuclide release into the circulating water, discharged into the bottom layer, during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.109) and (4.110)], and

(3) CDICRB(IPLT) as the specified constant coefficient for controlling the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant IPLT, representing the factor required for approximately considering the effect of the design and structural features of the discharge of plant IPLT [Eqs. (4.81), (4.110), and (4.112)].

21b. For the specified value of the integer control parameter IRBDPL(IPLT) = JDICRB(IPLT,IPER) = 1 (or > 0), which represents the user-specified option for determining the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant IPLT, based on the specified input data, PLANTS directly determines the transportive value of the bottom concentration of the radionuclide in the discharge flow CRBDIX [Eqs. (4.11) and (4.12)] based on

(1) CRBDPL(IPLT) = CRBDIS(IPLT,IPER) as the specified input data for the bottom concentration of the radionuclide associated with the discharge flow of plant IPLT, into the main flow channel, for the specified time period TPLPER(IPLT,IPER) [Eq. (4.111)] and

(2) CDICRB(IPLT) as the specified constant coefficient for controlling the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge

structure of plant IPLT, representing the factor required for approximately considering the effect of the design and structural features of the discharge of plant IPLT [Eqs. (4.81), (4.110), and (4.112)].

22. PLANTS calculates, for the element that contains the discharge IXPDIS(IPLT), at each intermediate time level T, the part representing the radionuclide transport, associated with the discharge flow of plant IPLT, discharged into the bottom layer in the main flow channel [Eq. (5.29d)] as the additional term to the value of the right-hand-side solution function (slope) FNCCRW(IXRDIS), which is stored in the labeled COMMON/CRWSOL/, for the solution of the water concentration of the radionuclide in the water layer CRW(IX) in the element IXRDIS= IXPDIS(IPLT) [Eq. (5.4a)].
23. PLANTS calculates, for the element that contains the discharge IXPDIS(IPLT), at each intermediate time level T, the part representing the radionuclide transport, associated with the discharge flow of plant IPLT, discharged into the bottom layer in the main flow channel [Eq. (5.29e)] as the additional term to the value of the right-hand-side solution function (slope) FNCCRB(IXRDIS), which is stored in the labeled COMMON/CRBSOL/, for the solution of the bottom concentration of the radionuclide in the bottom layer CRB(IX) in the element IXRDIS = IXPDIS(IPLT) [Eq. (5.5a)].

At the end of the computation stage, PLANTS completes all calculations, at the intermediate time level T, for all terms representing the transport associated with the intake and discharge flows of all plants IPLT = 1, ..., NPLT into or out of the main flow channel, which collectively represent the seventh step in the computational construction of all the right-hand-side solution functions for the solutions of all the principal solution variables in all elements and half-elements, according to the successive updating scheme, used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code; then, it returns to the modular subroutine SOLVER.

The structure and computational procedure of the modular subroutine PLANTS of the advanced development program version of the RADONE computer code were specifically designed to enable the user to understand, without undue difficulty, (1) the requirements for the preparation of the specified input data and (2) the computational algorithms associated with formulations of the temporally varying operational conditions of the plants that control the flow conditions and the radionuclide concentration conditions of the intake and discharge flows, into or out of the main flow channel, which are generally encountered in the applications of the computer code for the assessment of the radiological impact on the receiving water body that would result from accidental radiological release scenarios which can contaminate the discharge flows of plants, particularly nuclear power plants, operating on a river or an estuary. Hence, the structure of PLANTS reads and stores all specified sets of input data for (1) the operational conditions of all the plants and (2) all the specified time periods in the structurally separated part associated with the preparation stage of the subroutine. In certain applications of the RADONE computer code for continuous, long-term, and accurate simulations of the flow conditions and radionuclide concentration conditions in a controlled river or a tidal estuary during a relatively long period (e.g., six months), based on specified sets of input data with relatively high temporal resolution (e.g., 1 d or 1 h) for a large number of plants along the main flow channel, PLANTS could require substantial storage. Particularly in computer systems operating in an interactive, time-sharing mode, this excessive storage requirement of PLANTS could become a problem because excessive core storage allocations to the program could also reduce the overall computational speed of the complete system. This problem can (and should) be avoided by considering successive runs with the RADONE computer code for shorter simulation periods (e.g., one month) and only with the parts of the

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specified input data sets required for each particular simulation period. Because the RADONE computer code automatically includes the necessary restart capability, through the modular subroutines OUTPUT (Sect. 6.15) and the modular subroutine INITAL (Sects. 6.4 and 7.4), the user can (and should) separate the specified sets of input data for a relatively long simulation period (e.g., six months) into partial specified sets of input data for relatively shorter simulation periods (e.g., one month) and apply the code successively by restarting the computations for each successive, relatively shorter period.

The production program version of the RADONE computer code can completely eliminate the storage requirement for the specified sets of input data for each specified time period for the flow conditions and radionuclide concentration conditions of the intake and discharge flows, into or out of the main flow channel, of an operating plant by combining the preparation stage and the computation stage into a single computation stage in the modular subroutine PLANTS.

6.14 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE RADIOR

The modular subroutine RADIOR represents the simple computational algorithm for formulating the contribution of (1) the first-order radiological decay effect of the radionuclide in the water layer and (2) the first-order radiological decay effect of the radionuclide in the bottom layer to the solution of the radionuclide concentration conditions in the NX number of elements, according to the one-dimensional formulation of the discrete-element model of the RADONE computer code (Sects. 2, 3.8, and 5.2). RADIOR is the eighth (final) of the eight major modular subroutines that are called by the computational procedure of the modular subroutine SOLVER, according to the sequential computational method [Eqs. (5.30a) and (5.30b)], based on the successive updating scheme for the solution functions consisting of (1) $[F_{RAD}(\overline{C}_{rw})]_i$ in all N elements [Eqs. (2.12) and (5.30a)] and (2) $[F_{RAD}(\overline{C}_{rw})]_i$ in all N elements [Eqs. (2.21) and (5.30b)].

The structure and computational procedure of RADIOR (Fig. 6.14) consist of two operational stages, the preparation stage and the computation stage, which are initiated and completed, depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.14.1 Preparation Stage

RADIOR is first called from the MAIN program, with the value of the integer control parameter KRUN = 0 (Fig. 6.2), which is passed to the subroutine through the labeled COMMON/CONTRL/.

The preparation stage of RADIOR consists of a single operational step for reading the specified input data.

1. RADIOR reads (Fig. 6.14) the specified input data (Sect. 7.13) for the following information about the radiological decay effects:
   a. [RADNAM(ID), ID = 1,16] as the specified identification information for the radionuclide (Sects. 3.8 and 7.13) and
   b. THRHLF as the specified half-life of the radionuclide (as $t_{nuc}^{1/2}$) [Eq. (3.13)].

After reading the specified input data for first-order radiological decay conditions, which completes the preparation stage, RADIOR returns to the MAIN program.

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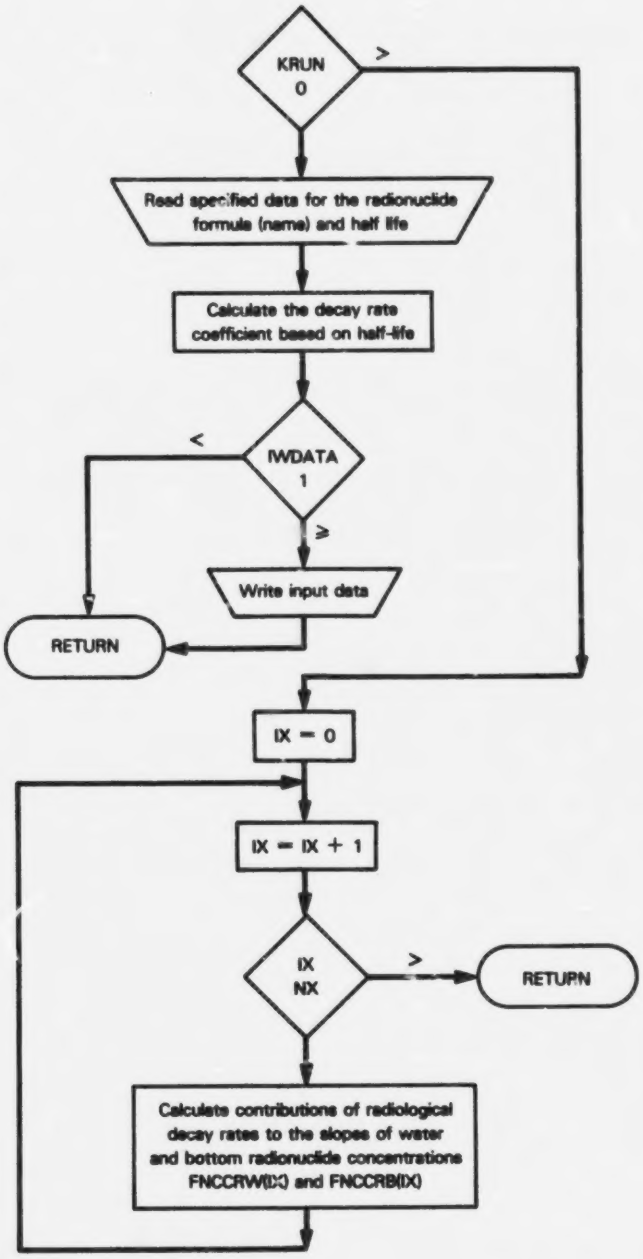
KRUN
0
>
Read specified data for the radionuclide formula (name) and half life
Calculate the decay rate coefficient based on half-life
<
IWDATA
1
≥
Write input data
RETURN
IX = 0
IX = IX + 1
IX
NX
>
RETURN
Calculate contributions of radiological decay rates to the slopes of water and bottom radionuclide concentrations FNCCRW(IX) and FNCCRB(IX)

Fig. 6.14. Abbreviated flowchart of the structure and computational procedure of the modular subroutine RADIOR of the RADONE computer code.

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6.14.2 Computation Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of the RADONE computer code, RADIOR is called by the modular subroutine SOLVER at every intermediate time level T of the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5).

The computation stage of RADIOR completes the eighth (final) step of the successive updating scheme [Eqs. (5.30a) and (5.30b)] used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code, by calculating the terms representing the contribution of the first-order radiological decay effects to the right-hand-side solution functions of the radionuclide concentrations in all the elements IX = 1, ..., NX, according to the following two operational steps (Fig. 6.14):

1. RADIOR calculates, at each intermediate time level T, the part representing the contribution of the first-order radiological decay effect [Eq. (5.30a)] as the additional term to the value of the right-hand-side solution function (slope) FNCCRW(IX), which is stored in the labeled COMMON/CRWSOL/, for the solution of water concentration of the radionuclide in the water layer CRW(IX) in the element IX [Eq. (5.4a)].
2. RADIOR calculates, at each intermediate time level T, the part representing the contribution of the first-order radiological decay effect [Eq. (5.30b)] as the additional term to the value of the right-hand-side solution function (slope) FNCCRB(IX), which is stored in the labeled COMMON/CRBSOL/, for the solution of bottom concentration of the radionuclide in the bottom layer CRB(IX) in the element IX [Eq. (5.5a)].

At the end of the computation stage, RADIOR completes the calculations, at the intermediate time level T, for all the terms associated with the contribution of the first-order radiological decay effects, which represent the eighth (final) step in the computational construction of the right-hand-side solution functions of the principal solution variables in all the elements, according to the successive updating scheme, used in the numerical integration (solution) of the governing system of discrete-element equations of the radionuclide transport model (Sect. 5.2) of the RADONE computer code; then, it returns to the modular subroutine SOLVER.

6.15 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE MODULAR SUBROUTINE OUTPUT

The modular subroutine OUTPUT coordinates all the different outputs, with different output formats and different output files, that represent the computer simulation results of the RADONE computer code for the principal solution variables of the radionuclide transport model (Sects. 2 and 5). The structure and the computational procedure of the modular subroutine OUTPUT (Figs. 6.15a and 6.15b) consist of three operational stages, (1) preparation stage, (2) intermediate output stage, and (3) final output stage, which are initiated and completed, depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.15.1 Preparation Stage

OUTPUT is first called from the MAIN program with the value of the integer control parameter KRUN = 0 (Fig. 6.2), which is passed to the subroutine through the labeled COMMON/CONTRL/. The preparation stage of OUTPUT consists of the following two operational steps (Fig. 6.15a):

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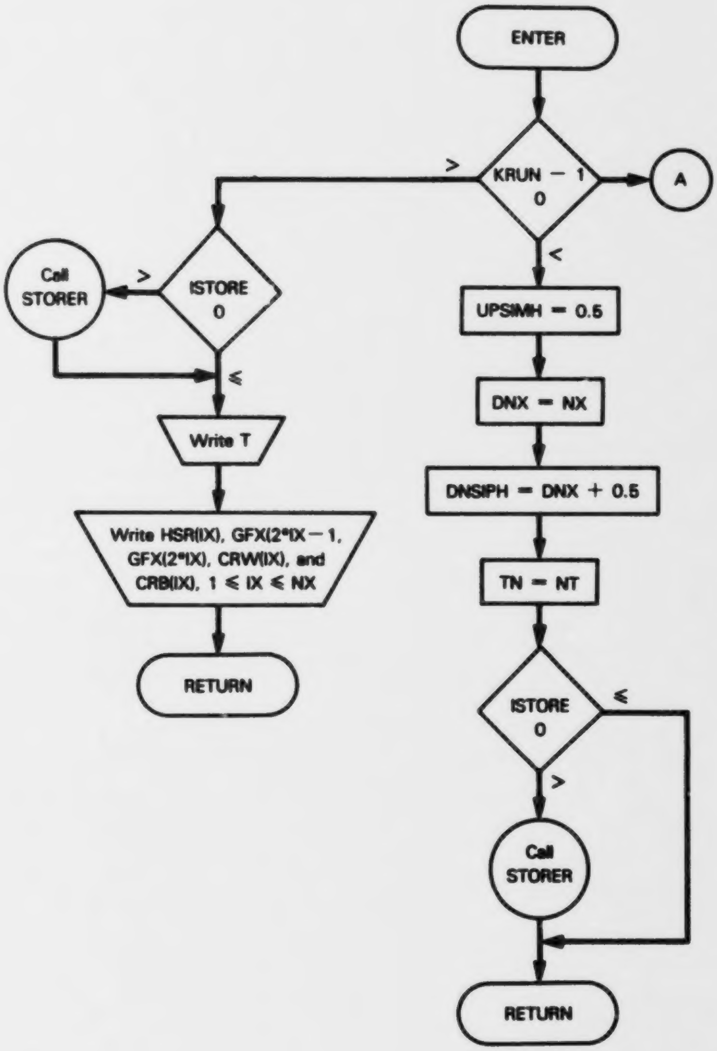
ENTER
KRUN − 1
0
>
<
A
ISTORE
0
>
≤
Call
STORER
Write T
Write HSR(IX), GFX(2*IX − 1, GFX(2*IX), CRW(IX), and CRB(IX), 1 ≤ IX ≤ NX
RETURN
UPSIMH = 0.5
DNX = NX
DNSIPH = DNX + 0.5
TN = NT
ISTORE
0
≤
>
Call
STORER
RETURN

Fig. 6.15a. Abbreviated flowchart of the structure and computational procedure of the modular subroutine OUTPUT of the RADONE computer code.

1. OUTPUT determines the values that indicate the locations of the upstream and downstream ends of the main flow channel in presenting the printed form of the computed results for the principal flow variables at the upstream- and downstream-end cross sections.
2. For the specified value of the integer control parameter ISTORE = 1 (or > 0), which is read in the MAIN program and passed to the subroutine through the labeled COMMON/PUTOUT/, as the user-specified option for storing the computed results for the principal flow variables, OUTPUT calls the modular subroutine STORER (Sect. 6.16).

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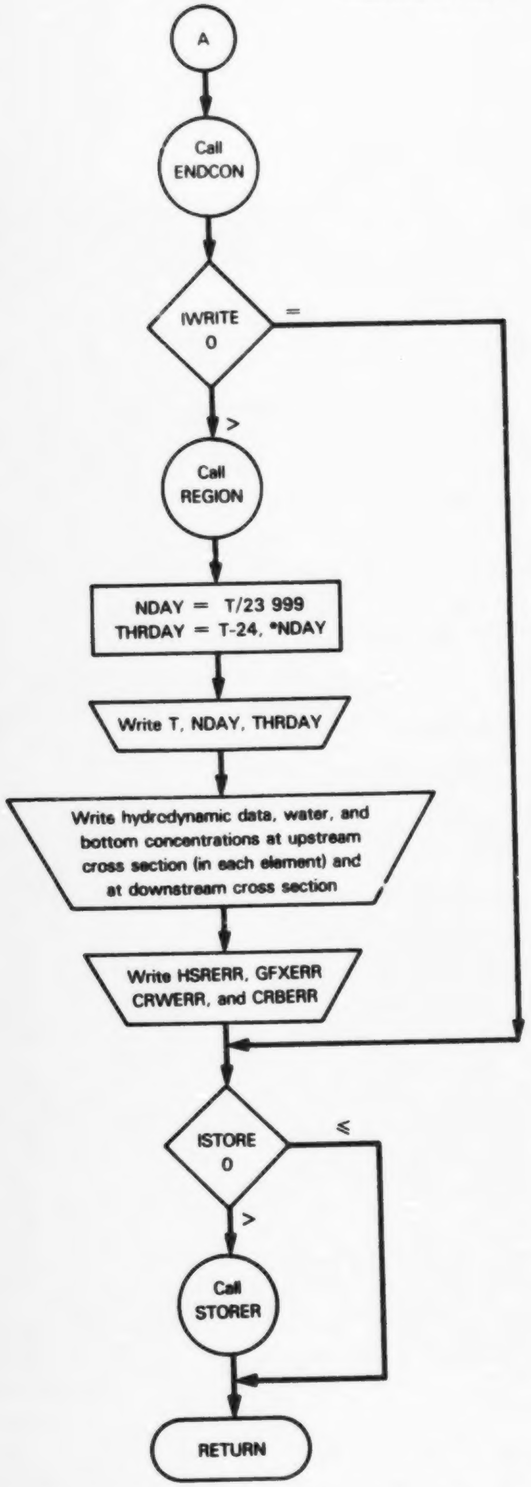
A
Call ENDCON
IWRITE 0
=
>
Call REGION
NDAY = T/23 999
THRDAY = T-24, *NDAY
Write T, NDAY, THRDAY
Write hydrodynamic data, water, and bottom concentrations at upstream cross section (in each element) and at downstream cross section
Write HSRERR, GFXERR CRWERR, and CRBERR
ISTORE 0
⩽
>
Call STORER
RETURN

Fig. 6.15b. Abbreviated flowchart of the structure and computational procedure of the modular subroutine OUTPUT of the RADONE computer code (continued).

After completing the two operational steps of the preparation stage, OUTPUT returns to the MAIN program.

6.15.2 Intermediate Output Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of the RADONE computer code, OUTPUT is called by the MAIN program after every NTW time step (Fig. 6.2b). OUTPUT writes, in different logical devices (files), in different output formats, the computed results according to the user-specified values of the integer control parameters IWRITE and ISTORE, which are read in the MAIN program and passed to the subroutine through the labeled COMMON/PUTOUT/.

The first part of the intermediate output stage of OUTPUT completes the calculations of the principal solution variables at the output time level T at the end of every NTW time step, according to the following two operational steps (Fig. 6.15a):

1. OUTPUT calls the modular subroutine ENDCON, which calculates and returns to OUTPUT the values of the principal solution variables at the upstream-end and downstream-end cross sections of the main flow channel at the intermediate output time level T at the end of every NTW time step, which is passed to the subroutine through the labeled COMMON/CONTRL/.
2. OUTPUT calls the modular subroutine REGION, which calculates and returns to OUTPUT the values of the detailed geometric properties of the cross sections of the elements of the main flow channel at the intermediate output time level T at the end of every NTW time step, based on the already calculated values of water surface elevation in the elements HSR(IX), IX = 1, ..., NX, which are passed to the subroutine through the labeled COMMON/HSRSOL/.

For the specified value of the integer control parameter IWRITE = 1 (or > 0), which is read in the MAIN program and passed through the labeled COMMON/PUTOUT/ and which indicates the user-specified option for printed output, OUTPUT initiates the second part of the intermediate output stage for preparing the printed output formats of the computed results for the principal flow variables of the solution, according to the following five operational steps (Fig. 6.15b):

3. OUTPUT calculates, according to the value of the intermediate output time level T at the end of every NTW time step, and writes in printed output format

   a. T as the intermediate output time level at the end of every NTW time step (hour),
   b. NDAY as the number of completed days corresponding to the intermediate output time level T at the end of every NTW time step, and
   c. THRDAY as the hour of the day after NDAY completed days corresponding to the intermediate output time level T at the end of every NTW time step (hour of the day).

4. Based on the computed results for the principal flow variables at the upstream-end enclosure surface of the main flow channel at IC = 1, which were already calculated in the modular subroutine ENDCON and passed to the subroutine through the labeled COMMON/ENDFLO/, OUTPUT calculates (if necessary) and writes, at the intermediate output time level T at the end of every NTW time step, in printed output format,

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   a. UPSIMH = 0.5, designating the upstream-end enclosure surface of the main flow channel,
   b. XC(1) as the location (along the curvilinear longitudinal *x*-axis of the main flow channel) of the upstream-end enclosure surface of the main flow channel (ft),
   c. DHSRMW as the difference between
      (1) water surface elevation HSRUPS at the upstream-end enclosure surface of the main flow channel and
      (2) HSRMWL as the representative mean water level for the total length TXLEST of the main flow channel, which is read in the modular subroutine ENDCON and passed to the subroutine through the labeled COMMON/CONEND/ (Sect. 6.6, ft),
   d. DHBUPS = HSC(1) as the depth at the upstream-end enclosure surface of the main flow channel, which is calculated in the modular subroutine REGION and passed to the subroutine through the labeled COMMON/GEOEST/ (ft),
   e. VFSUPS as the converted value of channel flow velocity at the upstream-end enclosure surface of the main flow channel (ft/s),
   f. GFSUPS as the converted value of channel flow rate at the upstream-end enclosure surface of the main flow channel (ft/s),
   g. CRWUPS as the water concentration of the radionuclide in the water layer at the upstream-end enclosure surface of the main flow channel (radiologic unit/ft^3), and
   h. CRBUPS as the bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface of the main flow channel (radiologic unit/ft^3).

5. Based on computed results for the principal solution variables in all elements IX = 1, ..., NX, in all upstream half-elements IMX = 2*IX − 1 = 1, 3, ..., 2*NX − 1 and in all downstream half-elements IPX = 2*IX = 2, 4, ..., 2*NX, which were already calculated in the modular subroutine SOLVER and passed to the subroutine through the labeled COMMON/HSRSOL/, COMMON/GFXSOL/, COMMON/CRWSOL/, and COMMON/CRBSOL/, OUTPUT calculates (if necessary) and writes, at the intermediate output time level T, at the end of every NTW time step, in printed output format, for all the elements IX = 1, ..., NX,

   a. IX designated the element,
   b. X(IX) as the location (along the curvilinear longitudinal *x*-axis of the main flow channel) of the element IX (ft),
   c. DHSRMW as the difference between
      (1) water surface elevation HSR(IX) in the element IX and
      (2) HSRMWL as the representative mean water level for the total length TXLEST of the main flow channel, which is read in the modular subroutine ENDCON and passed through the labeled COMMON/CONEND/ (Sect. 6.6) in the element IX (ft),
   d. DHBIII as the calculated depth in the element IX (ft),
   e. VFSIII as the calculated and converted value of channel flow rate in the element IX (ft/s),
   f. GFSIMX as the converted value of channel flow rate in the upstream half-element IMX = 2*IX − 1 (ft^3/s),
   g. GFSIII as the calculated and converted value of channel flow rate in the element IX (ft^3/s),
   h. GRSIPX as the converted value of channel flow rate in the downstream half-element IPX = 2*IX (ft^3/s),

   i. CRW(IX) as the water concentration of the radionuclide in the water layer in the element IX (radiologic unit/ft^3), and
   j. CRB(IX) as the bottom concentration of the radionuclide in the bottom layer in the element IX (radiologic unit/ft^3).

6. Based on computed results for the principal solution variables at the downstream-end enclosure surface of the main flow channel at IC = NC, which were already calculated in the modular subroutine ENDCON and passed to the subroutine through the labeled COMMON/ENDFLO/ (Sect. 6.6), OUTPUT calculates (if necessary) and writes, at the intermediate output time level T, at the end of every NTW time step, in printed output format,

   a. DNSIPH = NX + 0.5, designating the downstream-end enclosure surface of the main flow channel,
   b. XC(NC) as the location (along the curvilinear longitudinal *x*-axis of the main flow channel) of the downstream-end enclosure surface of the main flow channel (ft),
   c. DHSRMW as the difference between

      (1) water surface elevation HSRDNS at the downstream-end enclosure surface of the main flow channel and
      (2) HSRMWI as the representative mean water level for the total length TXLEST of the main flow channel, which is read in the modular subroutine ENDCON and passed to the subroutine through the labeled COMMON/CONEND/ (Sect. 6.6) (ft),

   d. DHBDNS = HSC(NC) as the depth at the downstream-end enclosure surface of the main flow channel, which is calculated in the modular subroutine REGION and passed to the subroutine through the labeled COMMON/GEOEST/ (ft),
   e. VFSDNS as the converted value of channel flow velocity at the downstream-end enclosure surface of the main flow channel (ft/s),
   f. GFSDNS as the converted value of channel flow rate at the downstream-end enclosure surface of the main flow channel (ft^3/s),
   g. CRWDNS as the water concentration of the radionuclide in the water layer at the downstream-end enclosure surface of the main flow channel (radiologic unit/ft^3), and
   h. CRBDNS as the bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface of the main flow channel (radiologic unit/ft^3).

7. Based on the values of the absolute norms of the truncation errors associated with the numerical integration, by the Runge-Kutta-Gill method [e.g., Conte and deBoor (1972)], of the principal solution variables, which are calculated in the MAIN program and passed to the subroutine through the labeled COMMON/HSRSOL/, COMMON/GFXSOL/, COMMON/CRWSOL/, and COMMON/CRBSOL/, OUTPUT writes, at the intermediate output time level T, at the end of every NTW time step,

   a. HSRERR as the absolute norm of the truncation error for water surface elevation (ft),
   b. GFXERR as the absolute norm of the truncation error for channel flow rate (ft^3/s),
   c. CRWERR as the absolute norm of the truncation error for water concentration of the radionuclide in the water layer (radiologic unit/ft^3), and
   d. CRBERR as the absolute norm of the truncation error for bottom concentration of the radionuclide in the bottom layer (radiologic unit/ft^3).

The second part of the intermediate output stage consists of the following operational step (Fig. 6.15b):

8. For the specified value of the integer control parameter ISTORE = 1 (or > 0), which is read in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/PUTOUT/, OUTPUT calls the auxiliary subroutine STORER (Sect. 6.16), which writes the computed results for the principal flow variables of the solution, according to special output formats for storing the information.

At the end of the intermediate output stage, the modular subroutine OUTPUT returns to the MAIN program.

6.15.3 Final Output Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 2, which indicates that all the computational procedures associated with the numerical integration of the principal solution variables have been completed in the RADONE computer code, OUTPUT is called again by the MAIN program during the termination stage (Sect. 6.2). OUTPUT writes the restart file, which corresponds indentically to the required set of specified input data for the modular subroutine INITAL (Sect. 6.4), according to the following operational step (Fig. 6.15a):

9. OUTPUT writes the restart file, according to the exact format of the specified set of input data for the modular subroutine INITAL (Sects. 6.4 and 7.4), for the last time level T of the computations, which is passed through the labeled COMMON/CONTRL/, and the final computed values of all the principal solution variables in all the elements IX = 1, ..., NX and in all the half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 2, 4, ..., 2*NX. These values consist of

    a. HSR(IX) as water surface elevation in the element IX, which is passed through the labeled COMMON/HSRSOL/,
    b. GFX(IMX) as channel flow rate in the upstream half-element IMX = 2*IX − 1, which is passed through the labeled COMMON/GFXSOL/,
    c. GFX(IPX) as channel flow rate in the downstream half-element IPX = 2+IX, which is passed through the labeled COMMON/GFXSOL/,
    d. CRW(IX) as water concentration of the radionuclide in the water layer in the element IX, which is passed through the labeled COMMON/CRWSOL/, and
    e. CRB(IX) as bottom concentration of the radionuclide in the bottom layer in the element IX, which is passed through the labeled COMMON/CRBSOL.

After completing the writing of the restart file in the final output stage, OUTPUT returns to the MAIN program.

6.16 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE AUXILIARY SUBROUTINE STORER

The auxiliary subroutine STORER is not an essential part of the general computational algorithm of the RADONE computer code. It is the first of the two auxiliary subroutines that are included in the advanced development program version of the RADONE computer code to provide the user with additional assistance in making cost-effective assessments of the radiological impact on the receiving water body that would result from accidental radiological release scenarios which can contaminate the discharges of operational plants along a river or an estuary.

STORER is included in the RADONE computer code for two reasons. First, in applications of the RADONE computer code to the assessment of the radiological impact on the receiving water body that would result from accidental radiological release scenarios which can contaminate the discharge flow conditions of numerous (or single) operational plants on a controlled river or a tidal estuary, it usually becomes necessary to consider numerous different radiological release scenarios associated with the operational conditions of numerous different plants for approximately the same hydrodynamic conditions in the main flow channel. Considering the stability criteria associated with the numerical integration of the principal solution variables (Sect. , it generally becomes computationally cost-effective to include, as specified input data, the water surface elevation HSR(IX) and channel flow rates GFX(IMX) and GFX(IPX), based on results of the already completed simulation without any operational plant (ambient conditions), in the subsequent additional simulations of (1) water concentration of the radionuclide in the water layer CRW(IX) and (2) bottom concentration of the radionuclide in the bottom layer CRB(IX) in all the elements IX = 1, ..., NX of the main flow channel for different specified radiological release scenarios associated with different plant operations. Second, in most applications of the RADONE computer code, it becomes necessary to consider various data reduction techniques for obtaining the necessary computer graphics representations of the numerical results either as spatial distributions or as temporal variations. The auxiliary subroutine STORER provides the user with the option for writing the results of the computer simulations according to special specified formats that could be used more conveniently in the reduction of the stored results and also in the preparation of the necessary computer graphics than the standard formats of the modular subroutine OUTPUT (Sect. 6.15 and 8.11).

The advanced development program version of the RADONE computer code includes the auxiliary subroutine STORER, which uses a special output format for rearranging the results of computer simulations as hourly variations on each day. This special output format was designed by considering the results of various applications of the RADONE computer code to the simulation of flow conditions and radionuclide concentration conditions in actual controlled rivers and tidal estuaries for the assessment of the radiological impact on the receiving water body that would result from different accidental radiological release scenarios associated with plant operations. Hence, it is important to point out that, for the specified value of the integer control parameter ISTORE = 1 (or > 0), which indicates the user-specified option for utilizing the auxiliary subroutine STORER, the specified input data for (1) NTW as the specified number of time steps between each successive output of the computed results and (2) DTHR (in hours) as the specified time step Δt_{RKG} of numerical integration (solution) must be selected to guarantee that the product of the two specified values is equal to 1 h.

The structure and computational procedure of the auxiliary subroutine STORER (Fig. 6.16) consist of two operational stages, the preparation stage and the intermediate output stage, which are initiated and completed depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.16.1 Preparation Stage

STORER is first called from the modular subroutine OUTPUT, for the specified value of the integer control parameter ISTORE = 1 (or > 0), which is read in the MAIN program and passed through the labeled COMMON/PUTOUT/ and which indicates the user-specified option for storing the computed results of the RADONE computer code for the principal solution variables (Fig. 6.15a), with the specified value of the integer control parameter KRUN = 0, which is passed through the labeled COMMON/CONTRL/.

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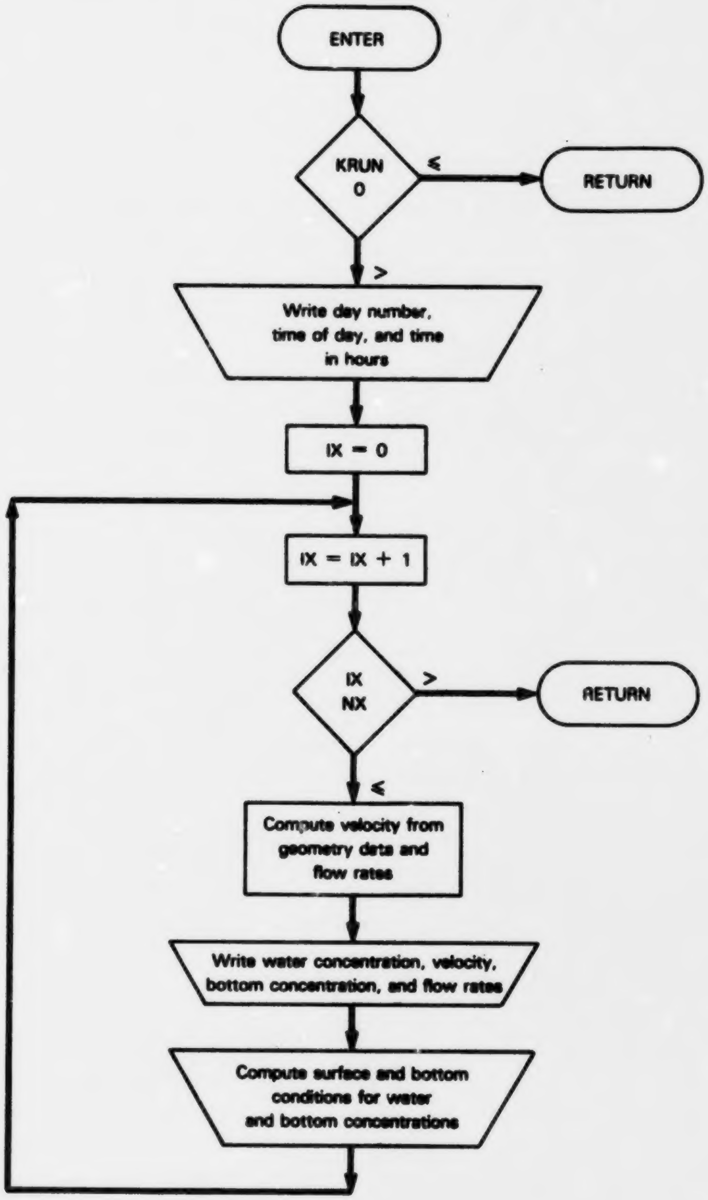
ENTER
KRUN
0
≤
RETURN
>
Write day number, time of day, and time in hours
IX = 0
IX = IX + 1
IX
NX
>
RETURN
≤
Compute velocity from geometry data and flow rates
Write water concentration, velocity, bottom concentration, and flow rates
Compute surface and bottom conditions for water and bottom concentrations

Fig. 6.16. Abbreviated flowchart of the structure and computational procedure of the modular subroutine STORER of the RADONE computer code.

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STORER initializes the value of the integer control parameter ISTART = 0, which indicates that a new set of output with special formats would be started for the computed results for the principal flow variables starting on the first day of the computer simulations; then, it returns to the modular subroutine OUTPUT.

6.16.2 Intermediate Output Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of the RADONE computer code, STORER is called from the modular subroutine OUTPUT, for the specified value of the integer control parameter ISTORE = 1 (or > 0), which is read in the MAIN program and passed to the subroutine through the labeled COMMON/PUTOUT/ and which indicates the user-specified option for storing the computed results for the principal solution variables after every NTW time step (Figs. 6.15b and 6.16).

The first part of the intermediate output stage of STORER completes the output for the day and the hour of the day corresponding to the appropriately selected intermediate output time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, at the end of the NTW time steps, according to the following two operational steps (Fig. 6.14):

1. Based on the value of the appropriately selected intermediate output time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, at the end of the NTW time steps, STORER calculates and writes NDAY as the day that includes the intermediate output time level T. It is important to note that the value of the output NDAY from STORER represents the day that includes the intermediate time level T; hence, its value is 1 d more than the value of the output NDAY of the printed output from the modular subroutine OUTPUT (Sect. 6.15).
2. Based on the value of the appropriately selected intermediate output time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, at the end of the NTW time steps, and the already calculated value of NDAY as the day that includes the intermediate time level T, STORER calculates and writes
    a. THRDAY as the hour of the day during the day NDAY,
    b. THRTOT as the value of the total number of hours corresponding to NDAY − 1 day and THRDAY hours, and
    c. T as the intermediate output time level.

It is important to note that the calculated value THRTOT, as the value of the total number of hours corresponding to NDAY − 1 day and THRDAY hours, must be equal (except for the truncation error) to the intermediate output time level T, which is passed through the labeled COMMON/CONTRL/, for the appropriately selected value of NTW, which is the number of time steps between the output of computed results at hourly intervals. Hence, the user should check the equivalence (except for the truncation error) of the values of THRTOT and T to ensure that the selected values for (1) DTHR (in hours) as the specified time step of the numerical integration (solution) of the governing system of discrete-element equations (Sect. 5.2) and (2) NTW as the specified number of time steps between each successive output of the computed results are appropriate for obtaining the desired hourly intervals of the output from STORER.

The second part of the intermediate output stage of STORER completes the output of the computed results for the principal solution variables in all the elements IX = 1, ..., NX in the main flow channel, according to the following operational step (Fig. 6.16):

3. STORER writes, according to the special output formats for storage, at the appropriately selected intermediate output time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/ and which corresponds to the time at the end of the 1-h interval after the NTW time steps, the computed results for the flow conditions and radionuclide concentration conditions in all the elements IX = 1, ..., NX and in all the half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 2, 4, ..., 2*NX. These conditions consist of

   a. IX designating the element,
   b. HSR(IX) as water surface elevation in the element IX, which is calculated in the modular subroutine SOLVER and passed to the subroutine through the labeled COMMON/HSRSOL/,
   c. GFX(IMX) as channel flow rate in the upstream half-element IMX = 2*IX − 1, which is calculated in the modular subroutine SOLVER and passed to the subroutine through the labeled COMMON/GFXSOL/,
   d. GFX(IPX) as channel flow rate in the downstream half-element IPX = 2*IX, which is calculated in the modular subroutine SOLVER and passed to the subroutine through the labeled COMMON/GRXSOL/,
   e. CRW(IX) as water concentration of the radionuclide in the water layer in the element IX, which is calculated in the modular subroutine SOLVER and passed to the subroutine through the labeled COMMON/CRWSOL/, and
   f. CRB(IX) as bottom concentration of the radionuclide in the bottom layer in the element IX, which is calculated in the modular subroutine SOLVER and passed to the subroutine through the labeled COMMON/CRBSOL/.

After completing the writing of a set of data for the flow conditions and radionuclide concentration conditions, at the appropriately selected intermediate output time level T corresponding to the time at the end of the 1-h interval after the NTW time steps, STORER reassigns the value of the integer control parameter ISTART = 1, which indicates that all subsequent sets of data for the flow conditions would be a part of the same, already started storage file; then, it returns to the modular subroutine OUTPUT.

It is important to point out again that the auxiliary subroutine STORER is not an essential part of the general computational algorithm of the RADONE computer code. It is included in the present advanced development program version of the RADONE computer code to enable the user to obtain special sets of the output results for the principal solution variables in the elements arranged as subsets with 25 records for the hourly values, starting at 00:00 h and ending at 24:00 h on each day of the computer simulations. The user can readily modify STORER to obtain the computed results for the principal solution variables, according to different output formats, without affecting the general computational structure and the operational procedure of the RADONE computer code, provided that (1) the modified subroutine retains the same forms for the labeled COMMON/ statements and (2) the new output formats of the subroutine are consistent with the formats of the specified input data to the auxiliary subroutine FLOWER (Sect. 6.17).

6.17 STRUCTURE AND COMPUTATIONAL PROCEDURE OF THE AUXILIARY SUBROUTINE FLOWER

The auxiliary subroutine FLOWER is not an essential part of the general computational algorithm of the RADONE computer code. It is the second of the two auxiliary subroutines that are included in the advanced development program version of the RADONE computer code to provide the user with additional assistance in making cost-effective assessments of the radiological impact on the receiving water body that would result from different accidental radiological release scenarios that could occur along a controlled river or a tidal estuary.

FLOWER is included in the advanced development program versions of all the fast-transient, one-dimensional mathematical transport models of the UTA project [e.g., Eraslan et al. (1976), Eraslan and Witten (1984)], including (1) ESTONE [Eraslan (1983)] of the thermal program, (2) SEDONE [Hetrick, Eraslan, and Patterson (1978)] of the sediment program, (3) CHMONE [Fischer et al. (1984)] of the chemical program, and (4) RADONE of the radiological program of this report.

FLOWER is included in the RADONE computer code as a user-specified option for excluding the solution of hydrodynamic conditions by incorporating the already computed and stored results for

1. water surface elevation HSR(IX) in the elements IX = 1, ..., NX,
2. channel flow rate GFX(IMX) in the upstream half-element IMX = 1, 3, ..., 2*NX − 1, and
3. channel flow rate GFX(IPX) in the downstream half-elements IPX = 2, 4, ..., 2*NX.

The present advanced development program version of the RADONE computer code includes the auxiliary subroutine FLOWER, which can incorporate directly, without any modification, the output of the computed results from the auxiliary subroutine STORER for hydrodynamic conditions at hourly intervals on each day of the computer simulations.

The structure and computational procedure of FLOWER (Figs. 6.17a–6.17d) consist of two operational stages, the preparation stage and the computation stage, which are initiated and completed, depending on the value of the integer control parameter KRUN, which is specified in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/.

6.17.1 Preparation Stage

FLOWER is first called from the MAIN program, for the specified value of the integer control parameter ICNFLO = 0 (or < 1), which indicates the user-specified option for excluding the solution of hydrodynamic conditions by incorporating specified input data for water surface elevation and channel flow rates in the main flow channel (Fig. 6.2a), with the specified value of the integer control parameter KRUN = 0, which is passed through the labeled COMMON/CONTRL/.

The preparation stage of FLOWER includes special provisions for aligning the time levels (1 h) of the specified input data for hydrodynamic conditions with the internally calculated time levels of the solution determined according to the general computational algorithm of the RADONE computer code. The internal computational algorithm of FLOWER automatically aligns the specified initial time (Sect. 6.4) with the appropriate specified time level of the specified input data for hydrodynamic conditions in the main flow channel in applications of the RADONE computer code with the specified value of the inter control parameter ICNFLO = 0 (or < 1), which indicates the user-specified option for excluding the solution of hydrodynamic conditions (Sect. 4.9). The preparation stage of FLOWER initiates and completes the necessary procedure for determining the appropriate specified time level (day and hour) and the specified input data for the hydrodynamic conditions that correspond to the specified initial time (Sect. 6.4), according to the following three operational steps (Fig. 6.17a):

1. Based on the specified value of the initial time T, which is read in the modular subroutine INITAL (Sect. 6.4) and passed to the subroutine through the labeled COMMON/CONTRL/, FLOWER calculates ITTDAY as the day that includes the initial time T.

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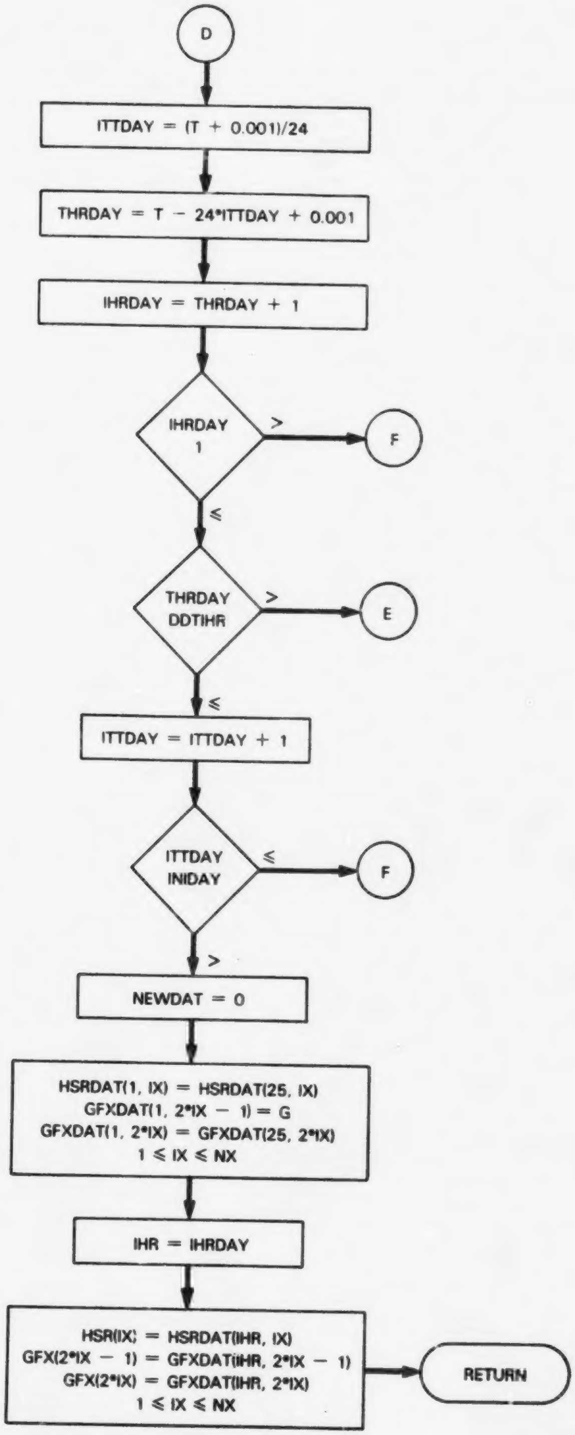
D
ITTDAY = (T + 0.001)/24
THRDAY = T − 24*ITTDAY + 0.001
IHRDAY = THRDAY + 1
IHRDAY
1
>
F
≤
THRDAY
DDTIHR
>
E
≤
ITTDAY = ITTDAY + 1
ITTDAY
INIDAY
≤
F
>
NEWDAT = 0
HSRDAT(1, IX) = HSRDAT(25, IX)
GFXDAT(1, 2*IX − 1) = G
GFXDAT(1, 2*IX) = GFXDAT(25, 2*IX)
1 ≤ IX ≤ NX
IHR = IHRDAY
HSR(IX) = HSRDAT(IHR, IX)
GFX(2*IX − 1) = GFXDAT(IHR, 2*IX − 1)
GFX(2*IX) = GFXDAT(IHR, 2*IX)
1 ≤ IX ≤ NX
RETURN

Fig. 6.17a. Abbreviated flowchart of the structure and computational procedure of the auxiliary subroutine FLOWER of the RADONE computer code.

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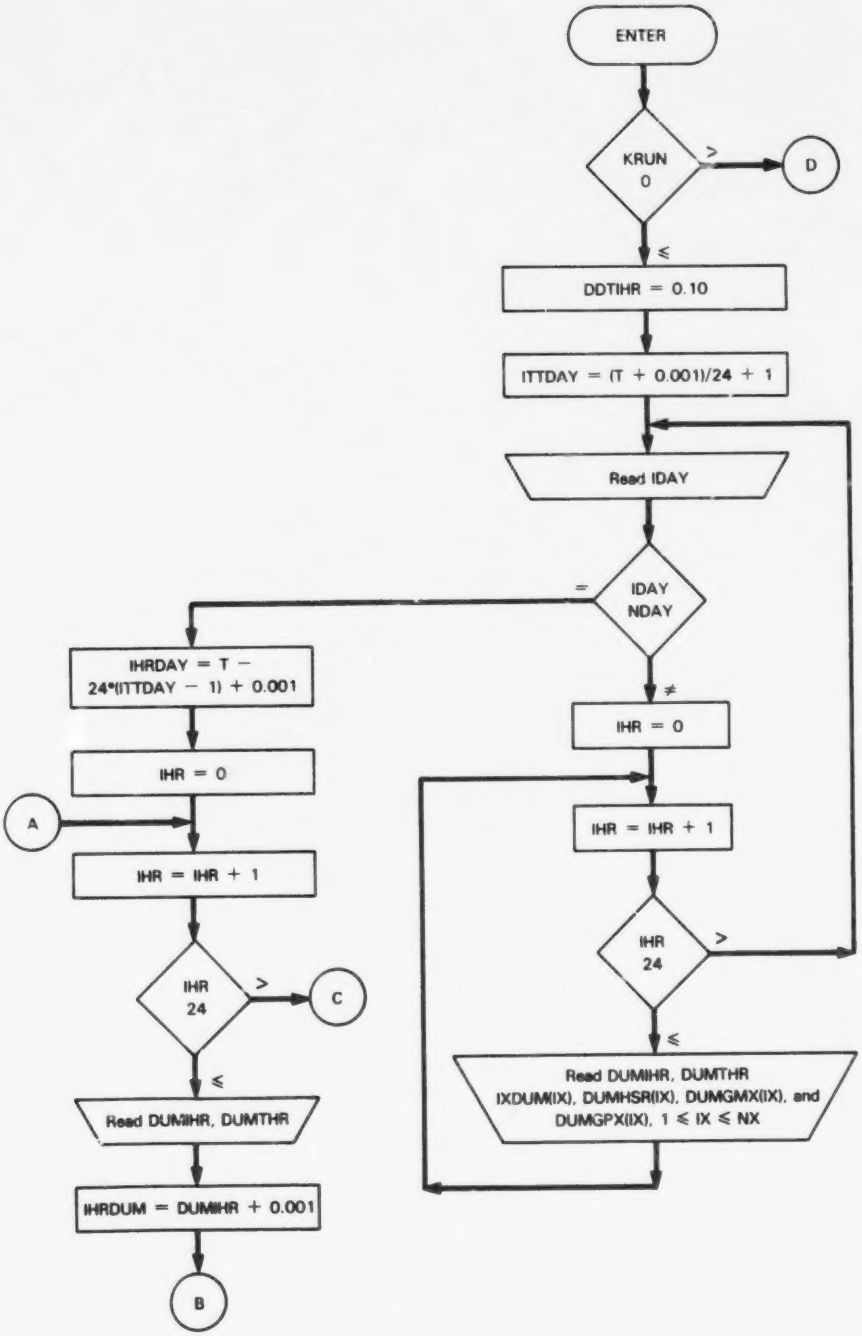
ENTER
KRUN
0
>
D
≤
DDTIHR = 0.10
ITTDAY = (T + 0.001)/24 + 1
Read IDAY
IDAY
NDAY
=
≠
IHRDAY = T − 24*(ITTDAY − 1) + 0.001
IHR = 0
A
IHR = IHR + 1
IHR
24
>
C
≤
Read DUMIHR, DUMTHR
IHRDUM = DUMIHR + 0.001
B
IHR = 0
IHR = IHR + 1
IHR
24
>
≤
Read DUMIHR, DUMTHR IXDUM(IX), DUMHSR(IX), DUMGMX(IX), and DUMGPX(IX), 1 ≤ IX ≤ NX

Fig. 6.17b. Abbreviated flowchart of the structure and computational procedure of the auxiliary subroutine FLOWER of the RADONE computer code (continued).

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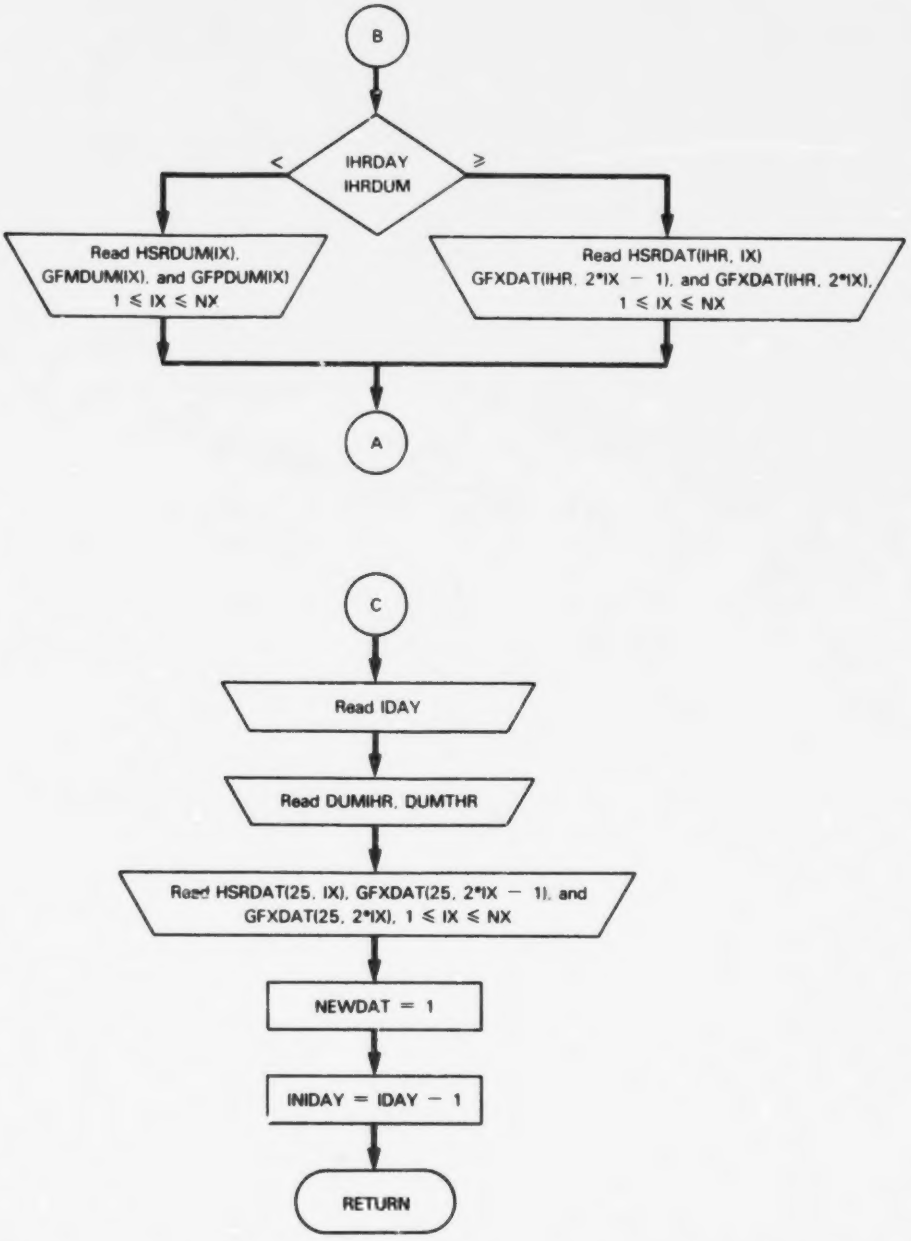
B
IHRDAY
IHRDUM
<
≥
Read HSRDUM(IX),
GFMDUM(IX), and GFPDUM(IX)
1 ≤ IX ≤ NX
Read HSRDAT(IHR, IX)
GFXDAT(IHR, 2*IX − 1), and GFXDAT(IHR, 2*IX),
1 ≤ IX ≤ NX
A
C
Read IDAY
Read DUMIHR, DUMTHR
Read HSRDAT(25, IX), GFXDAT(25, 2*IX − 1), and
GFXDAT(25, 2*IX), 1 ≤ IX ≤ NX
NEWDAT = 1
INIDAY = IDAY − 1
RETURN

Fig. 6.17c. Abbreviated flowchart of the structure and computational procedure of the auxiliary subroutine FLOWER of the RADONE computer code (continued).

ORNL-DWG 84-14057

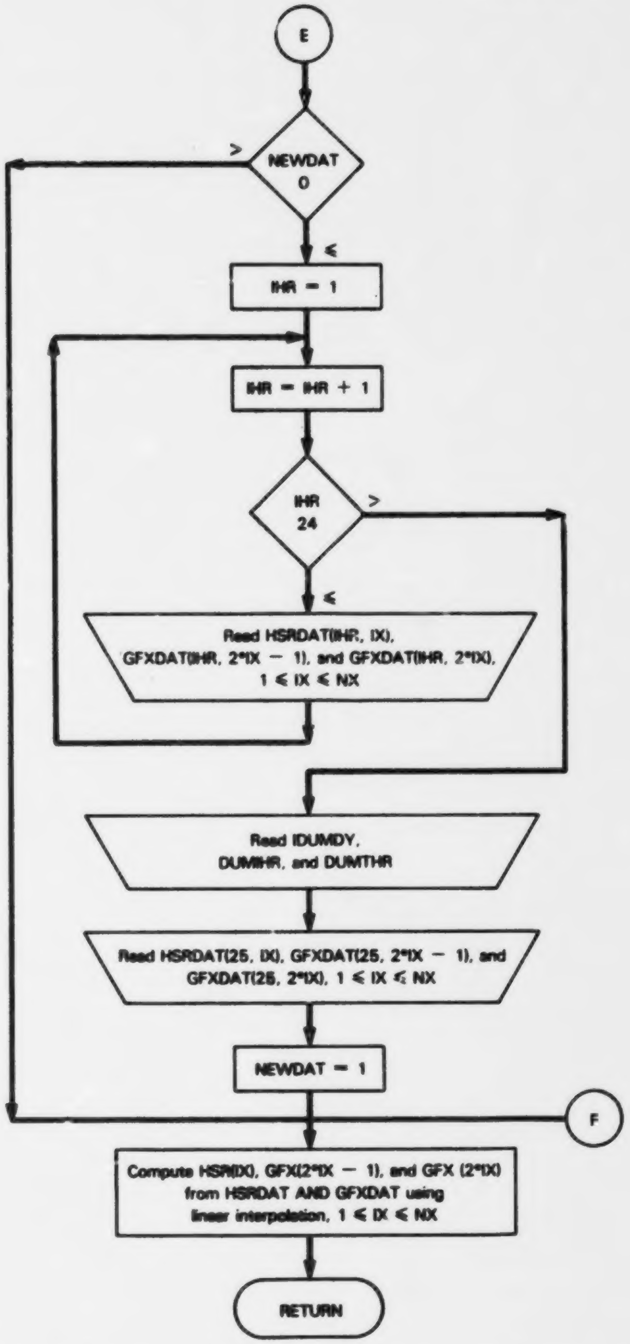
E
NEWDAT
0
>
≤
IHR = 1
IHR = IHR + 1
IHR
24
>
≤
Read HSRDAT(IHR, IX),
GFXDAT(IHR, 2*IX − 1), and GFXDAT(IHR, 2*IX),
1 ≤ IX ≤ NX
Read IDUMDY,
DUMIHR, and DUMTHR
Read HSRDAT(25, IX), GFXDAT(25, 2*IX − 1), and
GFXDAT(25, 2*IX), 1 ≤ IX ≤ NX
NEWDAT = 1
F
Compute HSR(IX), GFX(2*IX − 1), and GFX (2*IX)
from HSRDAT AND GFXDAT using
linear interpolation, 1 ≤ IX ≤ NX
RETURN

Fig. 6.17d. Abbreviated flowchart of the structure and computational procedure of the auxiliary subroutine FLOWER of the RADONE computer code (continued).

2. FLOWER reads continuously the consecutive records for IDAY as the specified day of the set of specified input data as the computed and stored results from the output of the auxiliary subroutine STORER (Sect. 6.16), for the hydrodynamic conditions in the main flow channel. If IDAY as the specified day of the specified input data for the hydrodynamic conditions is not equal to (less than) ITTDAY as the calculated day that includes the specified initial time T, FLOWER reads and discards as dummy data the next 25*(1 + 3*NX) data records, which represent DUMIHR as the hour of the day and the 25 hourly values for the hydrodynamic conditions in all the elements IX = 1, ..., NX and in all the half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 2, 4, ..., 2*NX.
3. If IDAY as the specified day of the specified input data for hydrodynamic conditions is equal to ITTDAY as the calculated day that includes the specified initial time T, FLOWER reads and stores the 25*(3*NX) values as the specified input data for hydrodynamic conditions in the main flow channel during the day by first reading and discarding as dummy data each DUMIHR as the hour of the day and, then, by reading and storing 25 hourly values in all the elements IX = 1, ..., NX and in all the half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 1, 2, ..., 2NX. These values consist of

    a. HSRDAT(IHR,IX) as the specified input data for water surface elevation at the hour of the day IHR in the element IX [Eq. (4.113)],

    b. GFXDAT(IHR,IMX) as the specified input data for channel flow rate at the hour of the day IHR in the upstream half-element IMX = 2*IX − 1 [Eq. (4.114a)], and

    c. GFXDAT(IHR,IPX) as the specified input data for channel flow rate at the hour of the day IHR in the downstream half-element IPX = 2*IX [Eq. (4.114b)].

At the end of the preparation stage, FLOWER determines all the 25 hourly values of the hydrodynamic conditions in all elements and half-elements of the main flow channel during the day ITTDAY, which includes the specified initial time T, which is read in the modular subroutine INITIAL and passed through the labeled COMMON/CONTRL/; then, it returns to the MAIN program.

6.17.2 Computation Stage

After the MAIN program reassigns the value of the integer control parameter KRUN = 1 and initiates the general computational procedure of the RADONE computer code, FLOWER is called by the modular subroutine SOLVER for the specified value of the integer control parameter ICNFLO = 0 (or < 1), which is read in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/ and which indicates the user-specified option for excluding the solution of hydrodynamic conditions by incorporating specified input data for the hydrodynamic conditions at every intermediate time level of the numerical integration (solution) of the governing system of discrete-element equations for water concentration of the radionuclide in the water layer CRW(IX) and bottom concentration of the radionuclide in the bottom layer CRB(IX) of the radionuclide transport model (Sect.5).

The first part of the computation stage of FLOWER determines (1) the appropriate specified day IDAY that includes the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, and (2) the specified input data for the 25 hourly values of hydrodynamic conditions in the main flow channel, according to the following three operational steps (Figs. 6.17b and 6.17c):

1. Based on the value of the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, FLOWER calculates ITTDAY as the day that includes the intermediate time level T.

2a. If ITTDAY is equal to the last read data record for IDAY as the specified day of the specified input data for hydrodynamic conditions, FLOWER retains the already stored 25*(3*NX) data records as the 25 hourly values of hydrodynamic conditions in all the elements IX = 1, ..., NX and the half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 2, 4, ..., 2*NX.

2b. If ITTDAY as the calculated day that includes the intermediate time level T is not equal to the last read data record for IDAY as the specified day of the specified input data for hydrodynamic conditions, FLOWER reads the next data record for IDAY in the set of specified input data for hydrodynamic conditions. It is important to note that, if ITTDAY as the calculated day is greater than the value of the last data record for IDAY as the specified input data for the hydrodynamic conditions, according to the special output of the auxiliary subroutine STORER (Sect. 6.16), the computation will automatically terminate with a FORTRAN error message indicating the "end of file" for the logical unit of the input device (Sect. 7.5).

3. For the new value of IDAY as the specified day of the specified input data for hydrodynamic conditions that includes the intermediate time level T, FLOWER reads the new values and replaces the stored 25*(3*NX) values with the new 25*(3*NX) values as the specified input data for hydrodynamic conditions in the main flow channel during the day by first reading and discarding as dummy data each DUMIHR as the hour of the day and, then, by reading and replacing the stored 25 hourly values in all the elements IX = 1, ..., NX and in all the half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 2, 4, ..., 2*NX. These data consist of

   a. HSRDAT(IHR,IX) as the specified input data for water surface elevation at the hour of the day IHR in the element IX,
   b. GFXDAT(IHR,IMX) as the specified input data for channel flow rate at the hour of the day IHR in the upstream half-element IMX = 2*IX − 1, and
   c. GFXDAT(IHR,IX) as the specified input data for channel flow rate at the hour of the day IHR in the downstream half-element IPX = 2*IX.

The last part of the computation stage of FLOWER calculates the hydrodynamic conditions at the intermediate time level T in all the elements IX = 1, ..., NX and in all the half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 2, 4, ..., 2*NX, based on linear interpolation between the hourly values of the specified input data for hydrodynamic conditions during the day, according to the following four operational steps (Fig. 6.16b):

4. Based on the value of the intermediate time level T, which is passed to the subroutine through the labeled COMMON/CONTRL/, FLOWER determines

   a. the hour of the day IHR, which is immediately before the intermediate time level T, and
   b. the hour of the day IHR + 1, which is immediately after the intermediate time level T.

5. FLOWER calculates the value, at the intermediate time level T, of water surface elevation HSR(IX) in the element IX, which is stored in the labeled COMMON/HSRSOL/, based on linear interpolation, with the constant specified time interval of 1 h, between

   a. HSRDAT(IHR,IX) as the specified input data for water surface elevation at the hour of the day IHR, which is immediately before the intermediate time level T, in the element IX, and
   b. HSRDAT(IHR + 1, IX) as the specified input data for water surface elevation at the hour of the day IHR + 1, which is immediately after the intermediate time level T, in the element IX [Eq. (4.115)].

6. FLOWER calculates the value at the intermediate time level T, of channel flow rate GFX(IMX) in the upstream half-element IMX = 2*IX − 1, which is stored in the labeled COMMON/GFXSOL/, based on linear interpolation, with the constant specified time interval of 1 h, between
   a. GFXDAT(IHR,IMX) as the specified input data for channel flow rate, at the hour of the day IHR, which is immediately before the intermediate time level T, in the upstream half-element IMX = 2*IX − 1, and
   b. GFXDAT(IHR + 1, IMX) as the specified input data for channel flow rate, at the hour of the day IHR + 1, which is immediately after the intermediate time level T, in the upstream half-element IMX = 2*IX − 1 [Eq. (4.116a)].
7. FLOWER calculates the value, at the intermediate time level T, of channel flow rate GFX(IPX) in the downstream half-element IPX = 2*IX, which is stored in the labeled COMMON/GFXSOL/, based on linear interpolation, with the constant specified time interval of 1 h, between
   a. GFXDAT(IHR,IPX) as the specified input data for channel flow rate at the hour of the day IHR, which is immediately before the intermediate time level T, in the downstream half-element IPX = 2*IX, and
   b. GFXDAT(IHR + 1, IX) as the specified input data for channel flow rate at the hour of the day IHR + 1, which is immediately after the intermediate time level T, in the downstream half-element IPX = 2*IX [Eq. (4.116b)].

At the end of the computation stage, the auxiliary subroutine FLOWER completes the calculations for the linear interpolation of hydrodynamic conditions, at the intermediate time level T, in all the elements IX = 1, .., NX and in all the half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 2, 4, ..., 2*NX; then, it returns to the modular subroutine SOLVER.

It is important to point out again that the auxiliary subroutine FLOWER is not an essential part of the general computational algorithm of RADONE. It is included in the present advanced development program version of the RADONE computer code as a user-specified option for excluding the solution of hydrodynamic conditions by incorporating already computed and stored results for water surface elevation and channel flow rates in the elements and half-elements of the main flow channel.

The auxiliary subroutine FLOWER of the advanced development program version of RADONE stores all 25 hourly values, on each day, of the hydrodynamic conditions in all elements and half-elements. Hence, FLOWER requires 25*(3*NX) stored values for hydrodynamic conditions, which is substantially more than the total storage requirement of the general computational algorithm of ESTONE for the numerical integration (solution) of all the principal solution variables. The storage requirement of FLOWER can be readily reduced to 2*(3*NX) by considering only two hourly values for the specified input data for the hydrodynamic conditions that are used in the linear interpolation of the hydrodynamic conditions at the intermediate time level T.

The user can readily modify or replace FLOWER for determining hydrodynamic conditions at the intermediate time level T, based on the specified input data, provided that the new modified or replaced auxiliary subroutine (1) retains the same forms for all the labeled COMMON/ statements and (2) includes new formats for the specified input data that are consistent with the formats of the output of the computed results from the auxiliary subroutine STORER (Sect. 6.16).

7. INPUT DATA TO THE RADONE COMPUTER CODE

The present "advanced development program" version of the RADONE computer code includes the MAIN program; ten modular subroutines REGION, INITAL, ENDCON, TURBUL, GROUND, BOTTOM, SURFAC, STREAM, PLANTS, and RADIOR; and the auxiliary subroutine FLOWER, which require user-specified input data (Sect. 6).

7.1 GENERAL DISCUSSION OF THE INPUT DATA

The RADONE computer code is specifically designed for applications to site-specific problems that require accurate simulations of transient, one-dimensional, hydrodynamic conditions, and two-layer radionuclide concentration conditions in a controlled river or a tidal estuary for the assessment of the radiological impact on the water body that would result from various realistic accidental radiological release scenarios that could occur in the geographic region of its main flow channel. Hence, the RADONE computer code includes all the capabilities necessary for incorporating accurate and detailed specified information about all geologic, hydrologic, climatological, and radiological conditions in the geographic region of a controlled river or a tidal estuary that can affect the flow conditions and radionuclide concentration conditions in its main flow channel. Furthermore, the RADONE computer code includes all the necessary capabilities for incorporating detailed specified input data for accurately representing the temporal variations of the flow conditions and radionuclide uptake and release conditions associated with the intake and discharge flows of the operating plants along a river or an estuary.

Each modular subroutine of the RADONE computer code, which requires specified input data for calculating the computational part associated with a particular type of transport phenomenon, is structured to read the complete set of its required specified input data within the subroutine (Sect. 6). Consistent with the fundamental computational concept of the Unified Transport Approach (UTA) [e.g., Eraslan et al. (1976), Eraslan and Witten (1984)], each set of required specified input data for each modular subroutine can be prepared or modified, completely independently, without altering any of the other sets of required specified input data for the MAIN program and other modular and auxiliary subroutines of the RADONE computer code.

Hence, the user can (and should) prepare one set of required specified input data for one modular subroutine at a time by completely disregarding the other sets of required specified input data for the other modular and auxiliary subroutines. Furthermore, after completing the preparation of one set of required specified input data for one modular subroutine, the user can (and should) check for possible errors in the completed data set by running the RADONE computer code for one time step NT = 1 with the specified value of the integer control parameter IWDATA = 1 (or > 0), which indicates the user-specified option for including the output of the specified input data sets. The systematic procedure for checking for possible errors in the sets of specified input data will be discussed in detail in subsequent sections, which present the input data formats for the MAIN program and the modular and auxiliary subroutines of the RADONE computer code.

It is important to emphasize that the user is not required to prepare extensive sets of specified input data for all modular subroutines of the RADONE computer code. Indeed, most of the modular subroutines include user-specified integer control parameters or simple data records that determine the detail and the amount of specified input data that would be supplied to the subroutines. The user has the option to prepare different sets of specified input data with different details and amounts for different modular subroutines. The user can implement the RADONE computer code without any restriction by using a simple set of

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minimum required specified input data for any one modular subroutine and by using extensive sets of detailed specified input data for all of the other modular subroutines. Also, the user can implement the RADONE computer code without any restrictions by using simple sets of minimum required specified input data for the modular subroutines in problems that do not require accurate and detailed simulations of flow conditions and radionuclide concentration conditions in the main flow channel. Hence, it is important to note that, although the RADONE computer code was specifically designed with the necessary capabilities for incorporating accurate and detailed specified input data for simulating accurately the hydrodynamic conditions and radionuclide concentration conditions in an actual controlled river or a tidal estuary, it can also be readily utilized with simple sets of minimum required specified input data for simulating approximately the flow conditions and radionuclide concentration conditions in any simple main flow channel.

All the modular and auxiliary subroutines of the RADONE computer code can read their independent sets of specified input data from different user-selected input devices designated by different logical unit numbers. According to the compilers of Digital Equipment Corporation (DEC) computer systems, the different sets of specified input data for the MAIN program and the subroutines can be arranged in any order because each subroutine can read directly its specific set of required specified input data from the different input devices designated by different logical unit numbers. In executing the RADONE computer code in other computer systems [e.g., IBM and Control Data Corporation (CDC)], special control instructions may be needed to establish the correct reading order of the different sets of the required specified input data to the MAIN program and the modular and auxiliary subroutines. If the user prefers to combine all of the different sets of required specified input data for the MAIN program and the modular and auxiliary subroutines into a single set of specified input data that can be read from a single input device with a single logical unit number, the READ statements of the program must be modified to include the same logical unit number, and the different sets of the specified input data must be arranged according to the sequential order shown in Table 7.1. The single combined set of required specified input data for the MAIN program and all the modular and auxiliary subroutines can be used directly in all large-scale computer systems. However, it is again emphasized that the user should check for possible errors in each

Table 7.1. Reading order and logical unit numbers of the input devices of the MAIN program and the modular subroutines of the RADONE computer code

Reading order of input data	MAIN program or subroutine	Logical unit number of selected input device
1	MAIN	user-selectable or (5)
2	REGION	user-selectable or (5)
3	INITAL	user-selectable or (5)
4	FLOWER[a]	user-selectable or (5)
5	ENDCON	user-selectable or (5)
6	TURBUL	user-selectable or (5)
7	BOTTOM	user-selectable or (5)
8	GROUND	user-selectable or (5)
9	SURFAC	user-selectable or (5)
10	STREAM	user-selectable or (5)
11	PLANTS	user-selectable or (5)
12	RADIOR	user-selectable or (5)

[a] Optional.

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part of the single, combined set of specified input data associated with each modular subroutine before attempting to execute the RADONE computer code for long-term computer simulations.

It is important to note that the MAIN program and all the modular and auxiliary subroutines of the RADONE computer code read the required sets of specified input data according to "fixed FORMAT" data records and not according to "free FORMAT" data records. All READ statements of the RADONE computer code were intentionally formulated to read according to fixed FORMAT data records to minimize the possibility of errors in preparation of the required sets of specified input data by a user who may not be familiar with the computer program. After becoming familiar with the present advanced development program version of ESTONE, the user can readily modify the READ statements to read according to free FORMAT data records.

Subsequent sections present in detail all sets of required specified input data used in the MAIN program and in all the modular and auxiliary subroutines of the RADONE computer code.

7.2 SPECIFIED INPUT DATA FOR THE MAIN PROGRAM

The MAIN program reads the required set of specified input data, from the input device, designated by the logical unit selected by the user, for the values of the parameters that control the computational procedure of the RADONE computer code (Sect. 6.2).

```
      READ(11,1001)NT,NTW,DTHR,ICNFLO,IWDATA,IWRITE,ISTORE
1001  FORMAT(2I6,F10.6,4I2)
```

NT = specified total number of time steps Δt_{RKG} that is used to determine the total duration of computer simulations by the Runge-Kutta-Gill numerical integration method (Sect. 5.3);

NTW = specified number of time steps between each successive output of the computed results (NTW must be less than or equal to NT);

DTHR = specified time step Δt_{RKG} of the Runge-Kutta-Gill numerical integration method based on the stability criteria of the numerical solution (Sect. 5.3, h);

ICNFLO = specified integer control parameter as the user-specified option for including or excluding the solution of hydrodynamic conditions (Sects. 4.9, 5.2, and 5.3);

= 0 as the user-specified option for excluding the solution of hydrodynamic conditions by incorporating specified input data for water surface elevation and channel flow rate according to the computational algorithm of the auxiliary subroutine FLOWER (Sects. 4.9, 5.2, 5.3, and 6.17). FLOWER is called in the preparation stage of the MAIN program (Sect. 6.2) and in the computation stage of the modular subroutine SOLVER at every intermediate time level of computations (Sect. 6.5);

= 1 as the user-specified option for including the solution of hydrodynamic conditions. The auxiliary subroutine FLOWER is not utilized.

IWDATA = specified integer control parameter as the user-specified option for including or excluding the printed output of all required sets of specified input data read by the modular and auxiliary subroutines;

= 0 as the user-specified option for excluding the printed output;

= 1 as the user-specified option for including the printed output.

IWRITE = specified integer control parameter as the user-specified option for including or excluding the detailed printed output of the computed results for all principal flow variables of the solution by the modular subroutine OUTPUT (Sect. 6.15);

= 0 as the user-specified option for excluding the detailed printed output;
= 1 as the user-specified option for including the detailed printed output.

ISTORE = specified integer control parameter as the user-specified option for including or excluding the special abbreviated form of output by the auxiliary subroutine STORER (Sect. 6.16) for the set of computed results for the auxiliary computer graphics programs and for special applications with hourly variations of hydrodynamic conditions that can be used as the required specified input data for the auxiliary subroutine FLOWER (Sect. 6.17);

= 0 as the use-specified option for excluding the special abbreviated form of output by the auxiliary subroutine STORER (Sect. 6.16), which is not utilized;
= 1 as the user-specified option for including the special abbreviated form of output by the auxiliary subroutine STORER (Sect. 6.16). STORER is called in the intermediate output stage of the modular subroutine OUTPUT at every intermediate output time level (Sect. 6.15).

In the application of the RADONE computer code to the simulation of detailed flow conditions and radionuclide concentration conditions in a controlled river or a tidal estuary, it is very important that the user prepare correctly all required sets of the specified input data for the modular subroutines. The user is strongly advised to check the required sets of specified input data for possible errors before attempting any long computer runs with the computer code. Hence, the user is advised to consider a special data record with NT = 1, NTW = 1, DTHR = 0, ICNFLO = 1, IWDATA = 1, and IWRITE = 1 for trial runs of the RADONE computer code; such trial runs will present detailed printed output of all the required sets of specified input data for all the modular subroutines. After the user becomes sure that all required sets of specified input data for all the modular subroutines are correct, the data record can be changed to include the appropriate values of the parameters that control the computational procedure of the RADONE computer code for long-term simulations of flow conditions.

7.3 SPECIFIED INPUT DATA FOR THE MODULAR SUBROUTINE REGION

The modular subroutine REGION reads the required set of specified input data, from the input device designated by the logical unit selected by the user, for the detailed geometric characteristics of the cross sections of the main flow channel (Sect. 6.3). The specified input data for the geometric characteristics of the cross sections of the main flow channel of an actual controlled-flow river or a tidal estuary can be obtained based on the bathymetry information on U.S. Coastal and Geodetic Survey Charts, which are available for most major navigable rivers and estuaries (Sects. 4.2 and 6.3).

```
      READ(12,1001)NC,TXLEST
1001  FORMAT(10X,I3,10X,E13.6)
```

NC = specified total number of cross-sectional transects used in specifying the detailed geometric data for the bed contour of the main flow channel at the locations corresponding to the

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locations of the upstream or downstream enclosure surfaces of the elements. The total number of cross-sectional transects includes the upstream-end and the downstream-end cross-sectional transects of the main flow channel. Hence, the total number of elements of the main flow channel NX = NC − 1 (Sects. 4.2 and 6.3);

TXLEST = specified total curvilinear longitudinal length of the main flow channel between the upstream-end cross-sectional transect IC = 1 and the downstream-end cross-sectional transect at IC = NC (ft).

```
      READ(12,1002)IRGEOM,HSRMAP
1002  FORMAT(8X,I2,4X,E13.6)
```

IRGEOM = specified integer control parameter for indicating the user-specified option for selecting the form of the trapezoidal integration scheme to be used in calculating the detailed geometric properties over the "core-area" and "embayment-area" part of the cross sections;

= 0 as the user-specified option for utilizing the simplified form of the trapezoidal integration scheme, based on linearized forms, in calculating the detailed geometric properties by considering only the variations over the embayment-area parts of the cross sections at every intermediate time level T of the computations. The detailed geometric properties are calculated by the trapezoidal integration scheme over the core-area parts of the cross section only one time, based on the specified mean water level for water surface elevation HSRMAP associated with the specified input data for the cross-sectional contours of the main flow channel; they are stored in the labeled COMMON/GEOMWL/. Subsequent calculations of the detailed geometric properties of the cross sections, at every intermediate time level T of the computations, only consider the variations of the detailed geometric properties over the embayment-area parts of the cross sections, based on the differences between water surface elevations at the intermediate time level T and the specified mean water level for water surface elevation HSRMAP (Sects. 4.2 and 6.3). If the variations of water surface elevations are expected to be much smaller than the depths of the cross sections of the main flow channel (i.e., if the embayment-area parts are expected to be much smaller than the core-area parts of the cross sections of the main flow channel), the user should select this option because the required computation times would be substantially reduced for calculations of the detailed geometric properties of the cross sections at every intermediate time level T of the computations;

= 1 as the user-specified option for utilizing directly the trapezoidal integration scheme in calculating the detailed geometric properties of the cross sections by integrating from the bottom, at the location of the maximum depth, to the water surface over the cross-sectional areas of the main flow channel at every intermediate time level T of the computations. This option should be used only when the variations of water surface elevations are expected to be comparable to the depths of the cross sections of the main flow channel (Sects. 4.2 and 6.3).

HSRMAP = specified map-reference mean water level for the main flow channel associated with the sets of specified input data for the detailed geometric conditions of the bed contours of the cross sections of the main flow channel (relative to the arbitrarily specified datum level for water surface elevation (Fig. 2.2, ft).

```
      DO 1100 IC=1,NC
      READ(12,1101)XC(IC),NZC(IC),HBC(IC)
1101  FORMAT(10X,E13.6,4X,I3,4X,E13.6)
      NZ = NZC(IC)
      DO 1110 LZ = 1,NZ
      READ(12,1111)Z(IC,LZ),YN(IC,LZ),YP(IC,LZ)
1111  FORMAT(10X,E13.6,2X,2,4X,E13.6)
1110  CONTINUE
1100  CONTINUE
```

The set of specified input data for the detailed geometric conditions of all of the cross-sectional transects IC = 1, ..., NC consists of

XC(IC) = specified distance (along the curvilinear longitudinal *x*-axis of the main flow channel) from an arbitrarily selected and specified origin of the *x*-axis to the location of each cross-sectional transect IC, which represents the location of the upstream or downstream enclosure surface of an element (Figs. 2.1 and 2.2, ft);

NZC(IC) = specified total number of positions along the "spatially relative" vertical coordinate Z of each cross-sectional transect IC (Figs. 3.1a–3.2b, 4.1a, and 4.1b) for specifying the data associated with the detailed geometric representation of the bed contour of the cross section of the main flow channel (ft);

HBC(IC) = specified elevation (relative to the arbitrarily specified datum level for water surface elevation (Fig. 2.2) of the bottom, at the location of maximum depth, of the cross-sectional transect IC of the main flow channel (ft).

The set of specified input data for the detailed geometric representation of the bed contour of each cross-sectional transect IC, for all the positions along the spatially relative vertical coordinate Z of the cross section LZ = 1, ..., NZ(IC) consists of

Z(IC,LZ) = specified vertical location along the spatially relative vertical coordinate Z of the cross section (Figs. 3.1a–3.2b, 4.1a, and 4.1b) for specifying the data associated with the bed contour of the main flow channel [Eqs. (4.1a) and (4.1b), ft];

YN(IC,LZ) = specified lateral location of the left bank of the bed contour of the main flow channel along the spatially relative lateral coordinate Y of the cross section (Figs. 3.1a–3.2b, 4.1a, and 4.1b) at the specified vertical location Z(IC,LZ) [Eq. (4.1a), ft];

YP(IC,LZ) = specified lateral location of the right bank of the bed contour of the main flow channel along the spatially relative lateral *y*-axis of the cross section (Figs. 3.1a–3.2b, 4.1a, and 4.1b) at the specified vertical location Z(IC,LZ) [Eq. (4.1b), ft].

REGION allows the user to specify the geometric representation of the bed contour of the main flow channel to any desired degree of accuracy. It is important to note that according to the computational algorithm of REGION, a single set of specified input data, LZ = NZ(IC) [for Z(IC,1), YN(IC,1), and YP(IC,1)], for the geometric representation of the bed contour of the cross-sectional transect IC, represents an inverted-triangular cross-sectional area with the apex corresponding to the location of HBC(IC) as the elevation of the bottom at the location of the maximum depth of the cross section. The user must include two sets of specified input data LZ = 1, ..., NX(IC), with NZ(IC) = 2, for the geometric representation of a rectangular cross-sectional area. The first set of specified input data for LZ = 1 must have Z(IC,1) = HBC(IC) as the elevation of the bottom at the location of the maximum depth of the cross section IC, with the specified lateral locations of the left bank YN(IC,1) and the right bank YP(IC,1) each equal to half of the width of the rectangle. The second set of specified input data for LZ = 2 must have Z(IC,2) as the specified vertical location equal to the sum of HBC(IC), as the elevation of the bottom at the location of maximum depth, and the height of the rectangle, with the same specified lateral location for the left bank YN(IC,2) = YN(IC,1) and the right bank YP(IC,2) = YP(IC,1). It is also important to note that the computational algorithm of REGION can consider only simply connected, single-cross-section bed contours of the main flow channel. The specified input data must combine the multiple areas of an actual cross section into an equivalent single cross section with a single, simply connected bed contour by eliminating the multiply connected embayment areas and/or islands in the main flow channel (Sect. 4.2).

7.4 SPECIFIED INPUT DATA FOR THE MODULAR SUBROUTINE INITAL

The modular subroutine INITAL reads the required set of specified input data, from the input device designated by the logical unit selected by the user, for determining the initial conditions for the principal solution variables in all elements and half-elements of the main flow channel (Sects. 5.2 and 6.4).

```
     READ(5,1001)ISTART,TSTART,HSRIII,GFXIMX,GFXIPS,CRWIII,CRBIII
1001 FORMAT(2X,I2,1X,E13.6,1X,E11.4,1X,2(1X,E11.4),1X,2(1X,E11.4))
```

ISTART = specified integer control parameter associated with selecting the user-specified option for determining initial conditions for the principal solution variables (Sects. 5.2 and 6.4);

= 0 as the user-specified option for using simplified initial conditions at the initial time T = 0. INITAL assumes that the values of any principal solution variable in the elements IX = 1, ..., NX or in the half-elements IMX = 1, 3, ..., 2*NX − 1 or IPX = 2, 4, ..., 2*NX are equal to the same reasonable approximate value that is specified as a single record data set. This user-specified option can be used conveniently when no information is available for the actual detailed initial conditions and when it is required to start the computer simulations from a specified set of hypothetical initial conditions, without requiring extensive preparations of the set of specified input data for the hypothetical initial conditions;

= 1 as the user-specified option for using actual detailed initial conditions at any specified initial time T with the complete set of specified input data for all principal solution variables in all the elements IX = 1, ..., NX and half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 2, 4, ..., 2*NX. This user-specified option is specifically designed for restarting computer simulations with the special restart set of specified input data that is automatically prepared by the modular subroutine OUTPUT (Sects. 6.15 and 8.11).

For the specified value of the integer control parameter ISTART = 1, which indicates the user-specified option for utilizing actual detailed initial conditions at the specified initial time T, the space beyond ISTART can be left blank on the data record.

For the specified value of the integer control parameter ISTART = 0, which indicates the user-specified option for utilizing simplified initial conditions at the initial time T = 0, the data record must be completed by including the following additional values for the principal solution variables (Sects. 5.2, 6.4, and 8.11):

HSRIII = specified reasonable, approximate value of water surface elevation HSR(IX) for all the elements IX = 1, ..., NX (ft);

GFXIMX = specified reasonable, approximate value of channel flow rate GFX(IMX) for all the upstream half-elements IMX = 1, 3, ..., 2*NX − 1 (ft^3/h);

GFXIPX = specified reasonable, approximate value of channel flow rate GFX(IPX) for all the downstream half-elements IPX = 2, 4, ..., 2*NX (ft^3/h);

CRWIII = specified reasonable, approximate value of water concentration of the radionuclide in the water layer CRW(IX) for all elements IX = 1, ..., NX (radiologic unit/ft^3);

CRBIII = specified reasonable, approximate value of bottom concentration of the radionuclide in the bottom layer CRB(IX) for all element IX = 1, ..., NX (radiologic unit/ft^3).

For specified value of the integer control parameter ISTART = 1, which indicates the user-specified option for using actual detailed initial conditions at the specified initial time T, INITAL reads additional sets of data.

```
      READ(19,2001)TSTART
2001  FORMAT(4X,E13.6)
```

TSTART = specified actual initial time (h).

```
      DO 2000 IX=1,NX
      IMX=2*IX--1
      IPX=IMX+1
      READ(5,2011)HSR(IX),GFX(IMX),GFX(IPX),CRW(IX),CRB(IX)
2011  FORMAT(19X,E11.4,1X,2(1X,E11.4),1X,2(1X,E11.4))
2000  CONTINUE
```

The set of specified input data for the actual detailed initial condition for all principal solution variables in all the elements IX = 1, ..., NX and half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 2, 4, ..., 2*NX consists of

HSR(IX) = specified water surface elevation in the element IX (ft);

GFX(IMX) = specified channel flow rate in the upstream half-element IMX = 2*IX − 1 (ft^3/h);

GFX(IPX) = the specified channel flow rate in the downstream half-element IPX = 2*IX (ft^3/h);

CRW(IX) = the specified water concentration of the radionuclide in the water layer in the element IX (radiologic unit/ft^3);

CRB(IX) = the specified bottom concentration of the radionuclide in the bottom layer in the element IX (radiologic unit/ft^3).

The modular subroutine INITAL allows the user to start the computer simulation of the RADONE computer code with any set of reasonable initial conditions for the principal solution variables in the main flow channel of a controlled river or a tidal estuary.

7.5 SPECIFIED INPUT DATA FOR THE AUXILIARY SUBROUTINE FLOWER

The auxiliary subroutine FLOWER reads the required set of specified input data, from the input device designated by the logical unit selected by the user, for the already computed and stored results for hydrodynamic conditions in all elements and half-elements of the main flow channel (Sects. 4.9, 5.2, and 6.17). The set of specified input data for FLOWER is only needed for the value of the integer control parameter ICNFLO = 0, which is read in the MAIN program and passed to the subroutine through the labeled COMMON/CONTRL/ and which indicates the user-specified option for excluding the solution of hydrodynamic conditions by incorporating directly, without any modification, the output of the computed results from the auxiliary subroutine STORER (Sects. 6.16 and 8.12) for the hydrodynamic conditions at hourly intervals on each day of the computer simulations. Hence, the user is never required to prepare the set of specified input data for FLOWER (Sects. 4.9 and 6.17).

The preparation stage of FLOWER includes special provisions for aligning the time levels (1 h) of the specified input data for hydrodynamic conditions with the specified initial time T, which is read in the modular subroutine INITAL (Sects. 6.4 and 7.4) and passed to the subroutine through the labeled COMMON/CONTRL/, based on ITTDAY as the day that includes the initial time T.

```
1000  READ(5,1001)IDAY
1001  FORMAT(2X,I4)
```

IDAY = specified day of the set of specified input data as the previously computed and stored results, from the output of the auxiliary subroutine STORER (Sect. 6.16), for hydrodynamic conditions in the elements and half-elements of the main flow channel.

```
      IF(IDAY.EQ.ITTDAY)GO TO 1500
      DO 1100 IHR=1,24
      READ(5,1101)DUMIHR,DMTHR
1101  FORMAT(2X,F7.2,1X,E13.6)
      DO 1110 IX=1,NX
      READ(5,1111)IXDUM,DUMHSP DUMGMX,DUMGPX
1111  FORMAT(1X,I3,E13.6,2(E11.4))
1110  CONTINUE
1100  CONTINUE
```

If IDAY as the specified day of the specified input data for hydrodynamic conditions is not equal to (is less than) ITTDAY as the calculated day that includes the specified initial time T, FLOWER reads and discards as dummy data the next 25*(1 + 3*NX) data records by considering the following dummy records (Sect. 6.17):

DUMIHR = dummy record for discarding 25 hourly values of the hour of the day IDAY;

IXDUM = dummy record for discarding 3*NX values of the hydrodynamic conditions in all elements IX = 1, ..., NX and half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 2, 4, ..., 2*NX at each hour of the day IDAY.

```
1500  CONTINUE
      TITDAY=ITTDAY-1
      IHRDAY=T-TITDAY*24.+0.001
      DO 1600 IHR=1,24
      READ(5,1601)DUMIHR,DUMTHR
1601  FORMAT(2X,F7.2,1X,E13.6)
      IHRDUM=DUMIHR+0.001
      IF(IHRDAY.LE.IHRDUM)GO TO 1650
      DO 1610 IX=1,NX
      READ(5,1611)HSRDUM,GFMDUM,GFPDUM
1610  CONTINUE
      GO TO 1600
1650  CONTINUE
      DO 1660 IX=1,NX
      IMX=2*IX-1
      IPX=IMX+1
      READ(5,1611)HSRDAT(IHR,IX),GFXDAT(IHR,IMX),GFXDAT(IHR,IPX)
1611  FORMAT(4X,E13.6,2(E11.4))
1660  CONTINUE
1600  CONTINUE
```

If IDAY as the specified day of the specified input data for hydrodynamic conditions is equal to ITTDAY as the calculated day that includes the specified initial time T, FLOWER reads and stores 25*(3*NX) values as the specified input data for hydrodynamic conditions in the main flow channel during the day by first reading and discarding as dummy data each hour of the day and then by reading and storing 25 hourly values in all elements IX = 1, ..., NX and in all half-elements IMX = 1, 3, ..., 2*NX − 1 and IPX = 2, 4, ..., 2*NX. This is done by considering the following data records (Sect. 6.17):

DUMIHR = dummy record for discarding 25 hourly values of the hour of day IDAY;

HSRDAT(IHR,IX) = specified water surface elevation at the hour of the day IHR in the element IX [Eq. (4.113), ft];

GFXDAT(IHR,IMX) = specified channel flow rate at the hour of the day IHR in the upstream half-element IMX = 2*IX − 1 [Eq. (4.114a), ft^3/h];

GFXDAT(IHR,IPX) = specified channel flow rate at the hour of the day IHR in the downstream half-element IPX = 2*IX [Eq. (4.114b), ft^3/h].

It is important to note that FLOWER reads the sets of specified input data for hydrodynamic conditions in the main flow channel according to the special output formats of the auxiliary subroutine STORER (Sects. 6.16 and 6.17). In applications of the present advanced development program version of the RADONE computer code, the user is not required to prepare any additional data for the hydrodynamic conditions, provided that the output formats of the auxiliary subroutine STORER and the input formats of the auxiliary subroutine FLOWER are retained as compatible (Sects. 6.16 and 6.17).

7.6 SPECIFIED INPUT DATA FOR THE MODULAR SUBROUTINE ENDCON

The modular subroutine ENDCON reads the required sets of specified input data from the input device designated by the logical unit selected by the user, for the temporal variations (or uniform conditions) of the principal solution variables at the upstream-end and downstream-end enclosure surfaces of the main flow channel (Sects. 4.3 and 6.6).

```
      READ(5,1001)IUPCON,IDNCON,HSRMWL
1001  FORMAT(10X,2(4X,I2),4X,E13.6))
```

IUPCON = specified integer control parameter for selecting the user-specified option for one of the three cases for upstream-end conditions of the main flow channel:

= 0 as the user-specified option for considering the case of simple closed-dam conditions at the upstream end of the main flow channel;
= 1 as the user-specified option for considering the case of controlled-flow dam conditions at the upstream end of the main flow channel;
= 2 as the user-specified option for considering the case of tidal flow conditions at the upstream end of the main flow channel.

IDNCON = specified integer control parameter for selecting the user-specified option for one of the three cases for downstream-end conditions of the main flow channel:

= 0 as the user-specified option for considering the case of simple closed-dam conditions at the downstream end of the main flow channel;
= 1 as the user-specified option for considering the case of controlled-flow dam conditions at the downstream end of the main flow channel;
= 2 as the user-specified option for considering the case of tidal flow conditions at the downstream end of the main flow channel.

HSRMWL = specified representative mean water level (relative to the arbitrarily specified datum level for water surface elevation, Fig. 2.2) for the total curvilinear longitudinal length of the main flow channel between the upstream-end enclosure surface and the downstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6, ft).

It is important to note that HSRMWL is the actual specified representative mean water level that is used in the actual computer simulations of flow conditions in the main flow channel; it is not necessarily equal to HSRMAP, which is read in the modular subroutine REGION as the specified map reference mean water level for the main flow channel, associated with the specified input data for detailed geometric conditions of the bed contours of the cross sections of the main flow channel (Sects. 4.2, 6.3, and 7.3).

```
     READ(5,1002)IUPCRW,CRWMNU,CRWMXU,IUPCRB,CRBMNU,CRBMXU
1002 FORMAT(4X,2(4X,I2,2X,E11.4,2X,E11.4))
     READ(5,1002)IDNCRW,CRWMND,CRWMXD,IDNCRB,CRBMND,CRBMXD
```

IUPCRW = specified integer control parameter for selecting the user-specified option for either specifying or internally determining water concentration of the radionuclide in the water layer at the upstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6);

= 0 as the user-specified option for internally determining water concentration of the radionuclide in the water layer at the upstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6);
= 1 as the user-specified option for determining water concentration of the radionuclide in the water layer at the upstream-end enclosure surface of the main flow channel based on specified input data.

CRWMNU = specified value of the minimum allowable water concentration of the radionuclide in the water layer at the upstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6, radiologic unit/ft^3).
CRWMXU = specified value of the maximum allowable water concentration of the radionuclide in the water layer at the upstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6, radiologic unit/ft^3).
IUPCRB = specified integer control parameter for selecting the user-specified option for either specifying or internally determining bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6);

= 0 as the user-specified option for internally determining bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6);
= 1 as the user-specified option for determining bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface of the main flow channel based on specified input data.

CRBMNU = specified value of the minimum allowable bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6, radiologic unit/ft^3).
CRBMXU = specified value of the maximum allowable bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6, radiologic unit/ft^3).
IDNCRW = specified integer control parameter for selecting the user-specified option for either specifying or internally determining water concentration of the radionuclide in the water layer at the downstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6);

= 0 as the user-specified option for internally determining water concentration of the radionuclide in the water layer at the downstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6);

= 1 as the user-specified option for determining water concentration of the radionuclide in the water layer at the downstream-end enclosure surface of the main flow channel based on specified input data.

CRWMND = specified value of the minimum allowable water concentration of the radionuclide in the water layer at the downstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6, radiologic unit/ft^3).

CRWMXD = specified value of the maximum allowable water concentration of the radionuclide in the water layer at the downstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6, radiologic unit/ft^3).

IDNCRB = specified integer control parameter for selecting the user-specified option for either specifying or internally determining bottom concentration of the radionuclide in the bottom layer of the downstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6);

= 0 as the user-specified option for internally determining bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6);

= 1 as the user-specified option for determining bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface of the main flow channel based on specified input data.

CRBMND = specified value of the minimum allowable bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6, radiologic unit/ft^3).

CRBMXD = specified value of the maximum allowable bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface of the main flow channel (Sects. 4.3 and 6.6, radiologic unit/ft^3).

For the specified value of the integer control parameter IUPCON = 1, which indicates the user-specified option for considering the case of controlled-flow dam conditions, ENDCON reads detailed specified input data for the upstream-end conditions (Sects. 4.3 and 6.6).

```
      READ(5,1101)NUPPER
1101  FORMAT(12X,I3)
```

NUPPER = specified number of time periods that would be used for specifying temporal variations (or temporally uniform conditions) of the principal solution variables at the upstream end of the main flow channel. At least one time period (i.e., NUPPER $\geqslant 1$) is required for specifying controlled-flow dam conditions at the upstream end of the main flow channel (Sects. 4.3 and 6.6).

```
       DO 1110 IPER=1,NUPPER
       READ(5,1111)TPRUPR(IPER),GFLUPR(IPER),VLXUPR(IPER),
     1                          CRWUPR(IPER),CRBUPR(IPER)
1111   FORMAT(8X,E13.6,2X,4(1X,E13.6))
1110   CONTINUE
```

ENDCON reads the specified set of input data as IPER = 1, ..., NUPPER list of records for the durations of the specified time periods and the detailed conditions for principal solution variables at the upstream end of the main flow channel. This data set consists of

TPRUPR(IPER) = specified time period for the specified upstream-end conditions (Sects. 4.3.2 and 6.6, h);

GFLUPR(IPER) = specified upstream-end channel flow rate (positive for flow into the main flow channel), during the specified time period TPRUPR(IPER) (Sects. 4.3.2 and 6.6, ft^3/h);

VLXUPR(IPER) = specified upstream-end channel flow velocity (positive along the positive direction of the curvilinear longitudinal *x*-axis of the main flow channel), during the specified time period TPRUPR(IPER) (Sects. 4.3.2 and 6.6, ft/h);

CRWUPR(IPER) = specified upstream-end water concentration of the radionuclide in the water layer, during the specified time period TPRUPR(IPER) (Sects. 4.3.2 and 6.6, radiologic unit/ft^3);

CRBUPR(IPER) = specified upstream-end bottom concentration of the radionuclide in the bottom layer, during the specified time period TPRUPR(IPER) (Sects. 4.3.2 and 6.6, radiologic unit/ft^3).

For the specified value of the integer control parameter IUPCRW = 0, which indicates the user-specified option for internally determining water concentration of the radionuclide in the water layer at the upstream-end enclosure surface (Sects. 4.3.4 and 6.6), the spaces allocated for CRWUPR(IPER) can be left blank because specified conditions for the upstream-end water concentration of the radionuclide in the water layer would not be used in the calculations of water concentration of the radionuclide in the water layer at the upstream-end enclosure surface. Similarly, for the specified value of the integer control parameter IUPCRB = 0, which indicates the user-specified option for internally determining bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface (Sects. 4.4 and 6.6), the spaces allocated for CRBUPR(IPER) can be left blank because specified conditions for the upstream-end bottom concentration of the radionuclide in the bottom layer would not be used in the calculations of bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface.

For the specified value of the integer control parameter IUPCON = 2, which indicates the user-specified option for considering the case of tidal flow conditions, ENDCON reads detailed specified input data for upstream-end conditions (Sects. 4.3 and 6.6).

```
      READ(5,1003)NHRTUP,NVRTUP,HSRTUP
1003  FORMAT(10X,I2,2X,I3,4X,E13.6)
```

NHRTUP = specified number of tidal harmonics (maximum of eight) of the upstream-end tidal variation of water surface elevation at the upstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6).

NVRTUP = specified number of time periods that would be used for specifying the nonharmonic temporal variations (or temporally uniform conditions) of the principal solution variables at the upstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6).

HSRTUP = specified constant upstream-end mean water surface elevation (mean water level relative to the arbitrarily specified datum level for water surface elevation, Fig. 2.2), representing the long-term constant, average value of water surface elevation at the upstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6, ft).

```
      DO 1010 IHRT=1,NHRTUP
      READ(5,1011)TIDTUP(IHRT),TLGTUP(IHRT),DHBTUP(IHRT)
1011  FORMAT(10X,3(4X,E13.6))
1010  CONTINUE
```

ENDCON reads the specified set of input data as IHRT = 1, ..., NHRTUP list of records for the specified tidal harmonic conditions at the upstream coastal open end of the main flow channel. This data set consists of

TIDTUP(IHRT) = specified period of the IHRT harmonic of the upstream-end tidal variation of water surface elevation of the upstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6, h);

TLGTUP(IHRT) = specified lag time (relative to midnight) of the IHRT harmonic of the upstream-end tidal variation of water surface elevation at the upstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6, h);

DHBTUP(IHRT) = specified amplitude of the IHRT harmonic of the upstream-end tidal variation of water surface elevation at the upstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6, ft).

```
       DO 1020 IVRT=1,NVRTUP
       READ(5,1021)PERTUP(IVRT),DHSRUP(IVRT),CRWMUP(IVRT),DCRWUP(IVRT),
     1                                   CRBMUP(IVRT),DCRBUP(IVRT)
1021   FORMAT(5X,E11.4,1X,E13.6,1X,2(1X,E11.4),1X,2(1X,E11.4))
1020   CONTINUE
```

ENDCON reads the specified set of input data as IVRT = 1, ..., NVRTUP list of records for the durations of the time periods and the specified detailed nonharmonic long-term variations of the principal flow variables at the upstream coastal open end of the main flow channel. This data set consists of

PERTUP(IVRT) = specified time period for the specified upstream coastal open end conditions (Sects. 4.3.3 and 6.6, h);

DHSRUP(IVRT) = specified upstream-end water surface elevation difference for representing the long-term variation of the upstream-end mean water surface elevation (mean water level relative to the arbitrarily specified datum level for water surface elevation, Fig. 2.2) relative to the specified constant upstream-end mean water surface elevation HSRTUP at the upstream coastal open end of the main flow channel, during the specified time period PERTUP(IVRT) (Sects. 4.3.3 and 6.6, ft);

CRWMUP(IVRT) = specified upstream-end average water concentration of the radionuclide in the water layer for representing the long-term variation of the mean water concentration of the radionuclide in the water layer (excluding the harmonic variations) in the coastal region at the upstream coastal open end of the main flow channel, during the specified time period PERTUP(IVRT) (Sects. 4.3.3 and 6.6, radiologic unit/ft^3);

DCRWUP(IVRT) = specified amplitude of the short-term periodic variation of the upstream-end water concentration of the radionuclide in the water layer in the coastal region at the upstream coastal open end of the main flow channel, during the specified time period PERTUP(IVRT) (Sects. 4.3.3 and 6.6, radiologic unit/ft^3);

CRBMUP(IVRT) = specified upstream-end average bottom concentration of the radionuclide in the bottom layer for representing the long-term variation of the mean bottom concentration of the radionuclide in the bottom layer (excluding the harmonic variations) in the coastal region at the upstream coastal open end of the main flow channel, during the specified time period PERTUP(IVRT) (Sects. 4.3.3 and 6.6, radiologic unit/ft^3);

DCRBUP(IVRT) = specified amplitude of the short-term periodic variation of the upstream-end bottom concentration of the radionuclide in the bottom layer in the coastal region at the upstream coastal open end of the main flow channel, during the specified time period PERTUP(IVRT) (Sects. 4.3.3 and 6.6, radiologic unit/ft^3).

For the specified value of the integer control parameter IUPCRW = 0, which indicates the user-specified option for internally determining water concentration of the radionuclide in the water layer at the upstream-end enclosure surface (Sects. 4.3.4 and 6.6), the spaces allocated for CRWMUP(IVRT) and DCRWUP(IVRT) can be left blank because specified conditions for the upstream-end water concentration of the radionuclide in the water layer would not be used in the calculations of water concentration of the radionuclide in the water layer at the upstream-end enclosure surface. Similarly, for the specified value of the integer control parameter IUPCRB = 0, which indicates the user-specified option for internally determining bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface (Sects. 4.4 and 6.6), the spaces allocated for CRBMUP(IVRT) and DCRBUP(IVRT) can be left blank because specified conditions for the upstream-end bottom concentration of the radionuclide in the bottom layer would not be used in the calculations of bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface.

For the specified value of the integer control parameter IDNCON = 1, which indicates the user-specified option for considering the case of controlled-flow dam conditions, ENDCON reads detailed specified input data for the downstream-end conditions (Sects. 4.3 and 6.6).

```
      READ(5,1301)NDNPER
1301  FORMAT(12X,I3)
```

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NDNPER = specified number of time periods that would be used for specifying the temporal variations (or temporally uniform conditions) of the principal solution variables at the downstream end of the main flow channel. At least one time period (i.e., NDNPER ≥ 1) is required for specifying controlled-flow dam conditions at the downstream end of the main flow channel (Sects. 4.3 and 6.6).

```
      DO 1310 IPER=1,NDNPER
      READ(5,1311)TPRDNR(IPER),GFLDNR(IPER),VLXDNR(IPER),
     1                          CRWDNR(IPER),CRBDNR(IPER)
1311  FORMAT(8X,E13.6,2X4(1X,E13.6))
1310  CONTINUE
```

ENDCON reads the specified set of input data as IPER = 1, ..., NDNPER list of records for the durations of the specified time periods and the detailed conditions for the principal solution variables at the downstream end of the main flow channel. This data set consists of

TPRDNR(IPER) = specified time period for the specified downstream-end conditions (Sects. 4.3.2 and 6.6, h);

GFLDNR(IPER) = specified downstream-end channel flow rate (positive for flow into the main flow channel), during the specified time period TPRDNR(IPER) (Sects. 4.3.2 and 6.6, ft^3/h);

VLXDNR(IPER) = specified downstream-end channel flow velocity (positive along the positive direction of the curvilinear longitudinal x-axis of the main flow channel), during the specified time period TPRDNR(IPER) (Sects. 4.3.2 and 6.6, ft/h);

CRWDNR(IPER) = specified downstream-end water concentration of the radionuclide in the water layer, during the specified time period TPRDNR(IPER) (Sects. 4.3.2 and 6.6, radiologic unit/ft^3);

CRBDNR(IPER) = specified downstream-end bottom concentration of the radionuclide in the bottom layer, during the specified time period TPRDNR(IPER) (Sects. 4.3.2 and 6.6, radiologic unit/ft^3).

For the specified value of the integer control parameter IDNCRW = 0, which indicates the user-specified option for internally determining water concentration of the radionuclide in the water layer at the downstream-end enclosure surface (Sects. 4.3.4 and 6.6), the spaces allocated for CRWDNR(IPER) can be left blank because specified conditions for the downstream-end water concentration of the radionuclide in the water layer would not be used in the calculations of water concentration of the radionuclide in the water layer at the downstream-end enclosure surface. Similarly, for the specified value of the integer control parameter IDNCRB = 0, which indicates the user-specified option for internally determining bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface (Sects. 4.4 and 6.6), the spaces allocated for CRBDNR(IPER) can be left blank because specified conditions for the downstream-end bottom concentration of the radionuclide in the bottom layer would not be used in the calculations of bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface.

For the specified value of the integer control parameter IDNCON = 2, which indicates the user-specified option for considering the case of tidal flow conditions, ENDCON reads detailed specified input data for the downstream-end conditions (Sects. 4.3 and 6.6).

```
      READ(5,1202)NHRTDN,NVRTDN,HSRTDN
1202  FORMAT(10X,I2,2X,I3,4X,E13.6)
```

NHRTDN = specified number of tidal harmonics (maximum of eight) of the downstream-end tidal variation of water surface elevation at the downstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6).

NVRTDN = specified number of time periods that would be used for specifying the nonharmonic temporal variations (or temporally uniform conditions) of the principal solution variables at the downstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6).

HSRTDN = specified constant downstream-end mean water surface elevation (mean water level relative to the arbitrarily specified datum level for water surface elevations, Fig. 2.2), representing the long-term constant average value of water surface elevation at the downstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6, ft).

```
      DO 1210 IHRT=1,NHRTDN
      READ(5,1211)TIDTDN(IHRT),TLGTDN(IHRT),DHBTDN(IHRT)
1211  FORMAT(10X,3(4X,E13.6))
1210  CONTINUE
```

ENDCON reads the specified set of input data as IHRT = 1, ..., NHRTDN list of records for the specified tidal harmonic conditions at the downstream coastal open end of the main flow channel. This data set consists of

TIDTDN(IHRT) = specified period of the IHRT harmonic of the downstream-end tidal variation of water surface elevation at the downstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6, h);

TLGTDN(IHRT) = specified lag time (relative to midnight) of the IHRT harmonic of the downstream-end tidal variation of water surface elevation at the downstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6, h);

DHBTDN(IHRT) = specified amplitude of the IHRT harmonic of the downstream-end tidal variation of water surface elevation at the downstream coastal open end of the main flow channel (Sects. 4.3.3 and 6.6, ft).

```
      DO 1220 IVRT=1,NVRTDN
      READ(5,1221)PERTDN(IVRT),DHSRDN(IVRT),CRWMDN(IVRT),DCRWDN(IVRT),
     1                                   CRBMDN(IVRT),DCRBDN(IVRT)
1221  FORMAT(5X,E11.4,1X,E13.6,1X,2(1X,E11.4),1X,2(1X,E11.4))
1220  CONTINUE
```

ENDCON reads the specified set of input data as IVRT = 1, ..., NVRTDN list of records for the durations of the time periods and the specified detailed nonharmonic long-term variations of the principal flow variables at the downstream coastal open end of the main flow channel. This data set consists of

PERTDN(IVRT) = the specified time period for specified downstream coastal open end conditions (Sects. 4.3.3 and 6.6, h);

DHSRDN(IVRT) = the specified downstream-end water surface elevation difference for representing the long-term variation of the downstream-end mean water surface elevation (mean water level relative to the arbitrarily specified datum level for water surface elevation, Fig. 2.2) relative to the specified constant downstream-end mean water surface elevation HSRTDN at the downstream coastal open end of the main flow channel, during the specified time period PERTDN(IVRT) (Sects. 4.3.3 and 6.6, ft);

CRWMDN(IVRT) = specified downstream-end average water concentration of the radionuclide in the water layer for representing the long-term variation of the mean water concentration of the radionuclide in the water layer (excluding the harmonic variations) in the coastal region at the downstream coastal open end of the main flow channel, during the specified time period PERTDN(IVRT) (Sects. 4.3.3 and 6.6, radiologic unit/ft^3);

DCRWDN(IVRT) = specified amplitude of the short-term periodic variation of the downstream-end water concentration of the radionuclide in the water layer in the coastal region at the downstream coastal open end of the main flow channel, during the specified time period PERTDN(IVRT) (Sects. 4.3.3 and 6.6, radiologic unit/ft^3);

CRBMDN(IVRT) = specified downstream-end average bottom concentration of the radionuclide in the bottom layer for representing the long-term variation of the mean bottom concentration of the radionuclide in the bottom layer (excluding the harmonic variations) in the coastal region at the downstream coastal open end of the main flow channel, during the specified time period PERTDN(IVRT) (Sects. 4.3.3 and 6.6, radiologic unit/ft^3);

DCRBDN(IVRT) = specified amplitude of the short-term periodic variation of the downstream-end bottom concentration of the radionuclide in the bottom layer in the coastal region at the downstream coastal open end of the main flow channel, during the specified time period PERTDN(IVRT) (Sects. 4.3.3 and 6.6, radiologic unit/ft^3).

For the specified value of the integer control parameter IDNCRW = 0, which indicates the user-specified option for internally determining water concentration of the radionuclide in the water layer at the downstream-end enclosure surface (Sects. 4.3.4 and 6.6), the spaces allocated for CRWMDN(IVRT) and DCRWDN(IVRT) can be left blank because specified conditions for the downstream-end water concentration of the radionuclide in the water layer would not be used in the calculations of water concentration of the radionuclide in the water layer at the downstream-end enclosure surface. Similarly, for the specified value of the integer control parameter IDNCRB = 0, which indicates the user-specified option for internally determining bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface (Sects. 4.4 and 6.6), the spaces allocated for CRBMDN(IVRT) and DCRBDN(IVRT) can be left blank because specified conditions for the downstream end bottom concentration of the radionuclide in the bottom layer would not be used in the calculations of bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface.

ENDCON allows the user to implement the RADONE computer code to problems that require accurate simulations of possibly reversing flow conditions in a river or a reservoir with detailed specified temporal variations of flow conditions at the upstream-end and/or downstream-end controlled-flow dams. Furthermore, it allows the user to implement the RADONE computer code in simulating accurately the tidal flow conditions in the main flow channel based on detailed specified multiharmonic tidal conditions at the upstream and/or downstream coastal open ends.

7.7 SPECIFIED INPUT DATA FOR THE MODULAR SUBROUTINE TURBUL

The modular subroutine TURBUL reads the required set of specified input data, from the input device designated by the logical unit selected by the user, for the calculations of nonconvective transport rates (convection-defect transport rates and eddy-turbulent transport rates, along the curvilinear longitudinal *x*-axis of the main flow channel) (Sects. 3.4 and 6.8).

```
      READ(5,1001)NFR,BETAFR,VISKIN,CCRWRB,VFLCRW,PPRVFL
1001  FORMAT(4X,I3,2(1X,E11.4),2X,2(1X,E11.4),1X,F5.2)
```

NFR = specified constant integer power of the Blasius power-law-type vertical distribution of channel flow velocity (suggested value as eight);

BETAFR = specified constant bottom friction coefficient, associated with the formulation of the nonconvective transport model, based on the Blasius power-law-type distribution of channel flow velocity (suggested universally constant value as 0.62);

VISKIN = specified constant (approximately) kinematic viscosity of mixed saline water (suggested value as 0.036 ft^2/h);

CCRWRB = specified constant parameter associated with the maximum vertical variation of the water concentration of the radionuclide in the water layer [Eqs. (3.56) and (3.57a)];

VFLCRW = specified constant reference value of channel flow speed associated with the reduction of the maximum vertical variation of the water concentration of the radionuclide in the water layer [Eqs. (3.56) and (3.57b), ft/h];

PPRVFL = specified constant power of the ratio of the local channel flow speed to the reference channel flow speed, associated with the maximum vertical variation of the water concentration of the radionuclide in the water layer [Eqs. (3.56) and (3.57c)].

It is important to note that the suggested values for the specified input data (Sect. 3.4) were determined based on preliminary simulation studies with the RADONE computer code and the ESTONE computer code [Eraslan (1983)] of the flow conditions and radionuclide concentration conditions in controlled-flow rivers and tidal estuaries. Hence, it is suggested that the user consider these values before assigning new values of the specified input data for the modular subroutine TURBUL in site-specific applications of the RADONE computer code to typical controlled-flow rivers and tidal estuaries.

7.8 SPECIFIED INPUT DATA FOR THE MODULAR SUBROUTINE GROUND

The modular subroutine GROUND reads the required set of specified input data, from the input device designated by the logical unit specified by the user, for groundwater seepage flow conditions into or out of the main flow channel in the geographic (climatological) region of a controlled-flow river or a tidal estuary (Sects. 4.6 and 6.9).

```
      READ(5,1001)ICNGRD,NGRPER
1001  FORMAT(10X,I2,2X,I4)
```

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ICNGRD = specified integer control parameter that represents the user-specified option for excluding or including the contribution of the transport associated with groundwater seepage flow into or out of the main flow channel to the solution of flow conditions and radionuclide concentration conditions in a controlled-flow river or a tidal estuary (Sects. 4.6 and 6.9);

= 0 as the user-specified option for excluding the contribution of the transport associated with groundwater seepage flow into or out of the main flow channel. For this user-specified option, GROUND terminates the reading of subsequent data records. Hence, the user is not required to prepare anv additional sets of specified input data;

= 1 as the user-specified option for including the contribution of the transport associated with groundwater seepage flow into or out of the main flow channel. For this user-specified option, GROUND continues the reading of the subsequent data records. Hence, the user is required to prepare additional sets of specified input data.

NGRPER = specified number of time periods for formulating the temporal variations of groundwater seepage flow conditions in the geographic (climatological) region of the main flow channel.

For the specified value of the integer control parameter ICNGRD = 1, which indicates the user-specified option for including the contribution of transport associated with groundwater seepage flow into or out of the main flow channel, GROUND reads the following sets of specified input data for groundwater seepage flow conditions in the geographic (climatological) region of a river or an estuary (Sects. 4.6 and 6.9).

```
      DO 1100 IX=1,NX
      READ(15,1101)CDFGRD(IX),POWGRD(IX),HGRHWT(IX),GRFAVG(IX),
     1            RBLGRD(IX)
1101  FORMAT(10X,E11.4,1X,E11.4,4X,E11.4,4X,E11.4,6X,E11.4)
1100  CONTINUE
```

The specified set of input data for geophysical conditions of the bed of the main flow channel in all elements IX = 1, ..., NX consists of

COFGRD(IX) = specified temporally constant coefficient of composite ground porosity associated with the formulation of hydrostatic groundwater seepage flux into or out of the main flow channel in the element IX [Eqs. (3.85) and (4.55), ft/h];

POWGRD(IX) = specified temporally constant power of the hydrostatic pressure gradient associated with the formulation of hydrostatic groundwater seepage flux into or out of the main flow channel in the element IX [Eqs. (3.85) and (4.57)];

HGRHWT(IX) = specified temporally constant average mean water surface elevation in the groundwater table (relative to the arbitrarily specified level associated with water surface elevation) for the element IX of the main flow channel [Eqs. (3.85) and (4.56), ft];

GRFAVG(IX) = specified temporally constant average groundwater seepage flow rate into or out of the element IX of the main flow channel [Eqs. (3.86) and (4.58), ft^3/h];

RBLGRD(IX) = specified temporally constant bottom-layer groundwater distribution along the curvilinear longitudinal *x*-axis of the main flow channel) factor for determining the groundwater seepage flow rate into or out of the bottom layer of element IX of the main flow channel, associated with the radionuclide transport rate into or out of the bottom layer, according to the groundwater seepage flow rate into or out of the main flow channel [Eqs. (3.89) and (4.59)].

```
      DO 1200 IPER=1,NGRPER
      READ(5,1201)DTGPER(IPER),DHWGRD(IPER),CFLGRD(IPER),
     1            CRWGRD(IPER),CRBGRD(IPER)
1201  FORMAT(6X,2(1X,E11.4),2X,3(1X,E11.4))
1200  CONTINUE
```

GROUND reads the specified set of input data as IPER = 1, ..., NGRPER list of records for the durations of the specified time periods and the detailed groundwater seepage flow conditions into or out of the main flow channel. This data set consists of

DTGPER(IPER) = specified time period for groundwater seepage flow conditions (Sects. 4.6 and 6.9, h);

GHWGRD(IPER) = specified difference in water surface elevation in the groundwater table relative to the specified, temporally constant, average mean water surface elevation GFRHWT(IX) in the geographic (climatological) region of the main flow channel, during the specified time period DTGPER(IPER) (Sects. 4.6 and 6.9, ft);

CFLGRD(IPER) = specified scaling factor associated with determining the temporal variation of the regional groundwater seepage flow into or out of the main flow channel, during the specified time period DTGPER(IPER) [Eqs. (3.84) and (4.60)];

CRWGRD(IPER) = specified water concentration of the radionuclide in the groundwater seepage flow into the water layer of the main flow channel, during the specified time period DTGPER(IPER) [Eq. (4.63), radiologic unit/ft^3];

CRBGRD(IPER) = specified bottom concentration of the radionuclide in the groundwater seepage flow into the bottom layer of the main flow channel, during the specified time period DTGPER(IPER) [Eq. (4.64), radiologic unit/ft^3].

In most applications of the RADONE computer code to the simulation of flow conditions and radionuclide concentration conditions in a typical large controlled-flow river or tidal estuary, the effect of groundwater seepage flow into or out of the main flow channel can be neglected. The user is advised to consider carefully groundwater conditions in the geographic (climatological) region of a controlled river or a tidal estuary in the preparation of specified sets of input data for the modular subroutine GROUND.

7.9 SPECIFIED INPUT DATA FOR THE MODULAR SUBROUTINE BOTTOM

The modular subroutine BOTTOM reads the required set of specified input data, from the input device designated by the logical unit selected by the user, for the bottom radionuclide transport conditions between the water layer and the bottom layer of the main flow channel (Sects. 3.5 and 6.10).

```
      READ(5,1001)ICNBOT
1001  FORMAT(10X,I2)
```

ICNBOT = specified integer control parameter that represents the user-specified option for excluding or including the contribution of the bottom radionuclide transport effect between the water layer and the bottom layer to the solution of the radionuclide concentration conditions in a controlled-flow river or a tidal estuary (Sects. 3.5 and 6.10);

= 0 as the user-specified option for excluding the contribution of the bottom radionuclide transport effect. For this user-specified option, BOTTOM terminates the reading of the subsequent data records. Hence, the user is not required to prepare any additional sets of specified input data;

= 1 as the user-specified option for including the contribution of the bottom radionuclide transport effect. For this user-specified option, BOTTOM continues the reading of the subsequent data records. Hence, the user is required to prepare additional sets of specified input data.

```
      READ(5,1002)DHBBED,CRFALL,VRFALL,VFLREF,PPFALL
1002  FORMAT(8X,1X,E11.4,2X,(3(1X,E11.4)),1X,F5.2)
      READ(5,1003)CCSUSP,ERDMOL,CCRTRB,CCRBOT
1003  FORMAT(8X,4(1X,E11.4))
```

DHBBED = specified constant depth of the bottom layer of the main flow channel [Eq. (2.16), ft];

CRFALL = specified constant coefficient of effective fall speed, associated with the lumped sediment-organic-matter class in the water layer [Eqs. (3.74) and (3.75a)];

VRFALL = specified constant effective fall velocity of the lumped sediment-organic-matter class, representing the average value of the fall velocities of all different classes of suspended sediment and all different suspended organic matter [Eqs. (3.74) and (3.75b), ft/h];

VFLREF = specified constant reference value of channel flow speed of settling reduction, associated with the overall inhibiting effect of local speed of flow on the settling (deposition) conditions of the lumped sediment-organic-matter class in the water layer [Eqs. (3.74) and (3.75c), ft/h];

PPFALL = specified constant power of the ratio of the local channel flow speed to the specified reference flow speed of settling reduction, associated with the overall inhibiting effect of the local speed of flow on the settling (deposition) rate of the lumped sediment-organic-matter class in the water layer [Eqs. (3.74) and (3.75d)];

CCSUSP = specified constant coefficient of resuspension, associated with the resuspension of the settled (deposited) sediment-organic-matter class from the bottom layer into the water layer [Eq. (3.79)];

ERDMOL = specified constant minimum bottom diffusion coefficient for evaluating the bottom-mixing radionuclide transport flux between the water layer and the bottom layer [Eqs. (3.72) and (3.73c), ft^2/h];

CCRTRB = specified constant coefficient of effective depth of mixing, for representing the inverse of the part (as percentage) of the local, average depth of water layer where the effective part of the eddy-turbulent mixing in the main flow channel controls the vertical transport of the radionuclide between the water layer and the bottom layer [Eqs. (3.72) and (3.73a)];

CCRBOT = specified constant coefficient of effective vertical eddy-turbulent mixing, representing the scaling factor required for obtaining the value of the effective eddy-turbulent mixing coefficient based on the value of the local, isotropic, cross-section-averaged coefficient of eddy-turbulent radionuclide transport [Eqs. (3.72) and (3.73b)].

It is important to note that the suggested values for the specified input data (Sect. 3.5) were determined based on preliminary simulations with the RADONE computer code and the SEDONE computer code [Hetrick, Eraslan, and Patterson (1978)] of the flow conditions, sediment concentration conditions, and radionuclide concentration conditions in controlled-flow rivers and tidal estuaries. Hence, it is suggested that the user consider these values before assigning new values of the specified input data for the modular subroutine BOTTOM in site-specific applications of the RADONE computer code to typical controlled-flow rivers and tidal estuaries.

7.10 SPECIFIED INPUT DATA FOR THE MODULAR SUBROUTINE SURFAC

The modular subroutine SURFAC reads the required set of specified input data, from the input device designated by the logical unit selected by the user, for the geometric conditions of the main flow channel and the temporal variations of the climatological conditions and radionuclide concentration conditions in the geographic (climatological) region of a controlled river or a tidal estuary, which control transport on the water surface of the main flow channel (Sects. 4.5 and 6.11).

```
     READ(5,1002)ICNSUR
1002 FORMAT(4X,I2)
```

ICNSUR = the specified integer control parameter that represents the user-specified option for excluding or including the contribution of transport at the water surface to the solution of flow conditions in the main flow channel of a controlled-flow river or a tidal estuary (Sect. 6.11);

= 0 as the user-specified option for excluding the contribution of transport at the water surface of the main flow channel. For this user-specified option, SURFAC terminates the reading of subsequent data records. Hence, the user is not required to prepare any additional sets of specified input data;

= 1 as the user-specified option for including the contribution of transport at the water surface of the main flow channel. For this user-specified option, SURFAC continues reading the subsequent data records. Hence, the user is required to prepare additional sets of specified input data.

For the specified value of the integer control parameter ICNSUR = 1, which indicates the user-specified option for including the contribution of transport at the water surface of the main flow channel, SURFAC reads the following sets of specified input data for the geometric conditions of the main flow channel, the temporal variations of climatological conditions, and the temporal variations of radionuclide concentration conditions in the geographic (climatological) region of a controlled river or a tidal estuary.

```
      DO 1100 IX=1,NX
      READ(5,1101)ADRSUR(IX),ESTDIR(IX)
1101  FORMAT(12X,2(4X,E13.6))
1100  CONTINUE
```

The specified set of input data for the geometric conditions of the main flow channel in all the elements IX = 1, ..., NX consists of

ADRSUR(IX) = specified drainage area in the geographic (climatological) region associated with drainage flow into the element IX of the main flow channel (Sects 4.4 and 6.11, ft);

ESTDIR(IX) = specified temporally constant angle of the direction of the curvilinear longitudinal *x*-axis of the main flow channel in the element IX relative to the arbitrarily specified geographic reference coordinate system; it is also used for specifying the direction of the wind in the geographic (climatological) region of the main flow channel [Sects. 4.4 and 6.11, degree (or radian)].

```
      READ(16,1001)NPRSUR,NHRSUR
1001  FORMAT(10X,I3,4X,I3)
```

NPRSUR = specified number of time periods for formulating the nonharmonic variations (or temporally uniform conditions) of the climatological conditions in the geographic (climatological) region of the main flow channel (Sects. 4.5 and 6.11);

NHRSUR = specified number (maximum of two) of harmonics (cosine) for formulating the short-term (within 1 d) harmonic variations of climatological conditions in the geographic (climatological) region of the main flow channel (Sects. 4.5 and 6.11).

At least one specified time period (i.e., NPRSUR ⩾ 1) and at least one harmonic (i.e., NHRSUR ⩾ 1) are required for specifying the temporal variations (or temporally uniform conditions) of climatological conditions and radionuclide concentration conditions in the geographic (climatological) region of a river or an estuary.

```
      DO 1200 IPER=1,NPER
      READ(5,1201)PERIOD(IPER)
1201  FORMAT(4X,E13.6)
      READ(5,1202)GRNAVG(IPER),GRNVAR(IPER,1),PERGRN(IPER,1),
     1                                          TLGGRN(IPER,1),
     2                          GRNVAR(IPER,2),PERGRN(IPER,2),
     3                                          TLGGRN(IPER,2)
1202  FORMAT(4X,E11.4,4X,2(2X,E11.4,2X,F6.2,2X,F6.2))
      READ(5,1203)WNDAVG(IPER),WNDVAR(IPER,1),PERWND(IPER,1),
     1                                       TLGWND(IPER,1),
     2                        WNDVAR(IPER,2),PERWND(IPER,2),
     3                                       TLGWND(IPER,2)
1203   FORMAT(4X,E11.4,2(4X,E11.4,2X,F7.2,2X,F6.2))
       READ(5,1204)DIRAVG(IPER),DIRVAR(IPER,1),PERDIR(IPER,1),
     1                                      TLGDIR(IPER,1),
     2                       DIRVAR(IPER,2),PERDIR(IPER,2),
     3                                      TLGDIR(IPER,2)
1204   FORMAT(4X,F7.2,2(4X,F7.2,2X,F7.2,2X,F6.2))
       READ(5,1205)CRDAVG(IPER),CRDVAR(IPER,1),PERCRD(IPER,1),
     1                                      TLGCRD(IPER,1),
     2                       CRDVAR(IPER,2),PERCRD(IPER,2),
     3                                      TLGCRD(IPER,2)
1205   FORMAT(4X,F7.2,2(4X,F7.2,2X,F7.2,2X,F6.2))
1200   CONTINUE
```

SURFAC reads the specified set of input data as IPER = 1, ..., NPER = NPRSUR list of records for the durations of the specified time periods and the detailed information for climatological conditions and radionuclide concentration conditions in the geographic (climatological) region of the main flow channel during the specified time periods. This data set consists of

PERIOD(IPER) = specified time period of the specified input data for the climatological conditions associated with the specifications of all transport (transfer) conditions at the water surface in the geographic (climatological) region of the main flow channel (Sects. 4.5 and 6.11);

GRNAVG(IPER) = specified average rainfall rate (per unit area) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, ft/h);

GRNVAR(IPER,IHRT=1,2) = specified amplitude of the IHRT harmonic (cosine) of the difference in rainfall rate (per unit area); used to represent the short-term variation of rainfall rate from the specified average rainfall rate GRNAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, ft/h);

PERGRN(IPER,IHRT=1,2) = specified period of the IHRT harmonic (cosine) of the difference in rainfall rate (per unit area); used to represent the short-term variation of rainfall rate from the specified average rainfall rate GRNAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, h);

TLGGRN(IPER,IHRT=1,2) = specified lag time of the IHRT harmonic (cosine) of the difference in rainfall rate (per unit area); used to represent the short-term variation of rainfall rate from the specified average rainfall rate GRNAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, hour of the day relative to midnight);

WNDAVG(IPER) = specified average wind speed in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, ft/h);

WNDVAR(IPER,IHRT=1,2) = specified amplitude of the IHRT harmonic (cosine) of the difference in wind speed; used to represent the short-term variation of wind speed from the specified average wind speed WNDAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, ft/h);

PERWND(IPER,IHRT=1,2) = specified period of the IHRT harmonic (cosine) of the difference in wind speed; used to represent the short-term variation of wind speed from the specified average wind speed WNDAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, h);

TLGWND(IPER,IHRT=1,2) = specified lag time of the IHRT harmonic (cosine) of the difference in wind speed; used to represent the short-term variation of wind speed from the specified average wind speed WNDAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, hour of the day relative to midnight);

DIRAVG(IPER) = specified average wind direction (relative to an arbitrarily specified geographic reference coordinate system that is also used for specifying the angle of direction of the main flow channel) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) [Sects. 4.5 and 6.11, degree (or radian)];

DIRVAR(IPER,IHRT=1,2) = specified amplitude of the IHRT harmonic (cosine) of the difference in wind direction (relative to an arbitrarily specified geographic reference coordinate system that is also used for specifying the angle of direction of the main flow channel); used to represent the short-term variation of wind direction from the specified average wind direction DIRAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) [Sects. 4.5 and 6.11, degree (or radian)];

PERDIR(IPER,IHRT=1,2) = specified period of the IHRT harmonic (cosine) of the difference in wind direction (relative to an arbitrarily specified geographic reference coordinate system that is also used for specifying the angle of direction of the main flow channel); used to represent the short-term variation of wind direction from the specified average wind direction DIRAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, h);

TLGDIR(IPER,IHRT=1,2) = specified lag time of the IHRT harmonic (cosine) of the difference in wind direction (relative to an arbitrarily specified geographic reference coordinate system that is also used for specifying the angle of direction of the main flow channel); used to represent the short-term variation of the wind direction from the specified average wind direction DIRAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, hour of the day relative to midnight);

CRDAVG(IPER) = specified average water concentration of the radionuclide in the rainfall in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, radiologic unit/ft^3);

CRDVAR(IPER,IHRT=1,2) = specified amplitude of the IHRT harmonic (cosine) of the difference in water concentration of the radionuclide in the rainfall; used to represent the short-term variation of water concentration of the radionuclide in the rainfall from the specified average water concentration of the radionuclide in the rainfall CRDAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, radiologic unit/ft^3);

PERCRD(IPER,IHRT=1,2) = specified period of the IHRT harmonic (cosine) of the difference in water concentration of the radionuclide in the rainfall; used to represent the short-term variation of water concentration of the radionuclide in the rainfall from the specified average water concentration of the radionuclide in the rainfall CRDAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, h);

TLGCRD(IPER,IHRT=1,2) = specified lag time of the IHRT harmonic (cosine) of the difference in water concentration of the radionuclide in the rainfall; used to represent the short-term variation of water concentration of the radionuclide in the rainfall from the specified average water concentration of the radionuclide in the rainfall CRDAVG(IPER) in the geographic (climatological) region of the main flow channel, during the specified time period PERIOD(IPER) (Sects. 4.5 and 6.11, hour of the day relative to midnight).

It is important to note that, for computer simulations that do not require detailed information for the climatological conditions and radionuclide concentration conditions, the user can implement the RADONE computer code with simplified conditions as approximately uniform values in the geographic (climatological) region of the main flow channel with a single-record specified data set with IPER = NPER = 1, which would be sufficient for the representations of long-term nonharmonic conditions. Furthermore, for computer simulations that do not require considerations of the short-term (within 1 d) harmonic variations of climatological conditions and radionuclide concentration conditions in the geographic region of the main flow channel, a single harmonic, with IHRT = NHRT = 1, and with zero values for the amplitudes of the first harmonics of all conditions, would be sufficient for eliminating all short-term (within 1 d) harmonic variations of the climatological conditions and radionuclide concentration conditions. The user is warned not to specify the period of any harmonic equal to zero in the sets of specified input data for climatological conditions or radionuclide concentration conditions in the geographic region of the main flow channel. For the user-specified cases of simulations with simplified specified input data for the climatological conditions and radionuclide concentration conditions, with the amplitudes of the first harmonics specified as zeros, the user should specify dummy nonzero values for all periods of the harmonics that have zero amplitudes in representing temporally uniform climatological conditions and radionuclide concentration conditions in the geographic (climatological) region of the main flow channel (Sects. 4.5 and 6.11).

7.11 SPECIFIED INPUT DATA FOR THE MODULAR SUBROUTINE STREAM

The modular subroutine STREAM reads the required set of specified input data, from the input device designated by the logical unit selected by the user, for the geometric conditions, detailed flow conditions, and radionuclide concentration conditions of the streams or tributaries flowing into or out of the main flow channel (Sects. 4.7 and 6.12).

```
      READ(5,1001)NSTREM
1001  FORMAT(10X,I3)
```

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NSTREM = specified number of streams or tributaries flowing into or out of the main flow channel.

For the specified value NSRM = NSTREM = 0, which indicates that no stream or tributary flows into or out of the main flow channel, STREAM terminates the reading of subsequent data records. Hence, the user is not required to prepare any additional set of specified input data.

For the specified number of streams or tributaries greater than zero, NSRM ⩾ 1, STREAM continues to read the subsequent sets of specified input data for flow conditions of streams or tributaries flowing into or out of the main flow channel of a river or an estuary.

```
      DO 1100 ISRM=1,NSRM
      READ(5,1101)(SRMNAM(ISRM,ID),ID=1,40),NRMPER(ISRM)
1101  FORMAT(10X,40A1,I4)
      READ(5,1102)IXCSRM(ISRM),JRMCRW(ISRM),JRMCRB(ISRM)
1102  FORMAT(6X,I4,1X,2(2X,I2))
1100  CONTINUE
```

The specified set of input data for the temporally constant conditions of streams or tributaries ISRM = 1, ..., NSRM along the main flow channel consists of

SRMNAM(ISRM,ID=1,40) = specified name (with a maximum of 40 letters) of stream or tributary ISRM along the main flow channel (Sect. 6.12);

NRMPER(ISRM) = specified number of time periods for formulating the temporal variations (or temporally uniform conditions) of flow conditions and radionuclide concentration conditions of stream or tributary ISRM into or out of the main flow channel (Sects. 4.7 and 6.10). At least one specified time period [i.e., NRMPER(ISRM) ⩾ 1] is required for each stream or tributary ISRM for specifying temporal variations (or temporally uniform conditions) of the flow conditions and radionuclide concentration conditions of the stream or tributary ISRM into or out of the main flow channel (h);

IXCSRM(ISRM) = specified element containing the connecting junction of stream or tributary ISRM along the curvilinear longitudinal *x*-axis of the main flow channel (Sects. 4.7 and 6.12);

JRMCRW(ISRM) = specified, temporally constant integer control parameter for determining water concentration of the radionuclide in the flow of stream or tributary ISRM into the water layer of the main flow channel (Sects. 4.7 and 6.12);

= 0 as the user-specified option for internally determining water concentration of the radionuclide in the flow of stream or tributary ISRM into the water layer of the main flow channel as the same as the water concentration of the radionuclide in the water layer in the element IXCSRM(ISRM), which contains the junction of stream or tributary ISRM along the curvilinear longitudinal *x*-axis of the main flow channel;

= 1 as the user-specified option for determining water concentration of the radionuclide in the flow of stream or tributary ISRM into the water layer of the main flow channel based on specified input data for formulating the temporal variations (or temporally uniform conditions) of water concentration of the radionuclide in the flow of stream or tributary ISRM into the water layer of the main flow channel.

JRMCRB(ISRM) = specified, temporally constant integer control parameter for determining bottom concentration of the radionuclide in the flow of stream or tributary ISRM into the bottom layer of the main flow channel (Sects. 4.7 and 6.12);

= 0 as the user-specified option for internally determining the bottom concentration of the radionuclide in the flow of stream or tributary ISRM into the bottom layer of the main flow channel as the same as the bottom concentration of the radionuclide in the bottom layer in the element IXCSRM(ISRM), which contains the junction of the stream or tributary ISRM along the curvilinear longitudinal *x*-axis of the main flow channel;

= 1 as the user-specified option for determining the bottom concentration of the radionuclide in the flow of stream or tributary ISRM into the bottom layer of the main flow channel based on specified input data for formulating the temporal variations (or temporally uniform conditions) of bottom concentration of the radionuclide in the flow of stream or tributary ISRM into the bottom layer of the main flow channel.

```
      DO 1200 ISRM=1,NSRM
      NPER=NRMPER(ISRM)
      DO 1210 IPER=1,NPER
      READ(5,1211)TRMPER(ISRM,IPER),GFLSRM(ISRM,IPER),
     1            VLXSRM(ISRM,IPER),CRWSRM(ISRM,IPER),CRBSRM(ISRM,IPER)
 1211 FORMAT(10X,5(1X,E13.6))
 1210 CONTINUE
 1200 CONTINUE
```

The modular subroutine STREAM reads the specified set of input data as IPER = 1, ..., NPER = NRMPER(ISRM) list of records for the durations of the specified time periods and the detailed information about flow conditions and radionuclide concentration conditions of all streams or tributaries ISRM = 1, ..., NSRM flowing into or out of the main flow channel of a river or an estuary. This data set consists of

TRMPER(ISRM,IPER) = specified time period of the specified input data for conditions of the flow of stream or tributary ISRM into or out of the main flow channel (Sects. 4.7 and 6.12, h);

GFLSRM(ISRM,IPER) = specified flow rate of stream or tributary ISRM into or out of the main flow channel, during the specified time period TRMPER(ISRM,IPER) (Sects. 4.7 and 6.12, ft^3/h);

VLXSRM(ISRM,IPER) = specified velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the flow of a stream or tributary ISRM into or out of the main flow channel, during the specified time period TRMPER(ISRM,IPER) (Sects. 4.7 and 6.12). If the information is not available for specifying the value of the velocity of stream or tributary ISRM, the data record for the specified velocity can be left blank, indicating approximately negligible velocity (along the curvilinear longitudinal *x*-axis of the main flow channel), for the flow into the main flow channel during the specified time period TRMPER(ISRM,IPER) (ft/h);

CRWSRM(ISRM,IPER) = specified water concentration of the radionuclide in the flow of stream or tributary ISRM into the water layer of the main flow channel, during the specified time period TRMPER(ISRM,IPER) (Sects. 4.7 and 6.12). If the information is not available for specifying the value of water concentration of the radionuclide in the flow of stream or tributary ISRM, the data record for the specified water concentration of the radionuclide can be left blank, indicating that the water concentration of the radionuclide in the flow of stream or tributary ISRM into the water layer of the main flow channel is approximately equal to the water concentration of the radionuclide in the water layer of the element IXCSRM(ISRM), which contains the connecting junction of the stream or tributary ISRM, by specifying the value of the integer control parameter for determining water concentration of the radionuclide in the flow of stream or tributary ISRM into the water layer of the main flow channel as JRMCRW(ISRM) = 0 (radiologic unit/ft^3);

CRBSRM(ISRM,IPER) = specified bottom concentration of the radionuclide in the flow of stream or tributary ISRM into the bottom layer of the main flow channel, during the specified time period TRMPER(ISRM,IPER) (Sects. 4.7 and 6.12). If the information is not available for specifying the value of bottom concentration of the radionuclide in the flow of stream or tributary ISRM, the data record for the specified bottom concentration of the radionuclide can be left blank, indicating that the bottom concentration of the radionuclide in the flow of stream or tributary ISRM into the bottom layer of the main flow channel is approximately equal to the bottom concentration of the radionuclide in the bottom layer of the element IXCSRM(ISRM), which contains the connecting junction of the stream or tributary ISRM, by specifying the value of the integer control parameter for determining bottom concentration of the radionuclide in the flow of the stream or tributary ISRM into the bottom layer of the main flow channel as JRMCRB(ISRM) = 0 (radiologic unit/ft^3).

It is important to note that, for computer simulations that do not require detailed information for the flow conditions and radionuclide concentration conditions of streams or tributaries into or out of the main flow channel, the user can implement the RADONE computer code with simplified specified input data for any stream or tributary ISRM, with a single-record specified input data set, with IPER = NRMPER(ISRM) = 1, which would be sufficient for representing the approximate temporally uniform flow conditions and radionuclide concentration conditions of stream or tributary ISRM into or out of the main flow channel.

7.12 SPECIFIED INPUT DATA FOR THE MODULAR SUBROUTINE PLANTS

The modular subroutine PLANTS reads the required set of specified input data, from the input device designated by the logical unit selected by the user, for the geometric conditions, detailed operational conditions and radionuclide concentration conditions associated with the plants located along the main flow channel (Sects. 4.8 and 6.13).

```
      READ(5,1001)NPLANT
1001  FORMAT(10X,I3)
      NPLT=NPLANT
```

NPLANT = specified number of plants located along the main flow channel.

For the specified value NPLT = NPLANT = 0, which indicates that no plants are located along the main flow channel, PLANTS terminates the reading of subsequent data records. Hence, the user is not required to prepare any additional set of specified input data.

For the specified number of plants greater than zero, NPLT ⩾ 1, PLANTS continues to read subsequent sets of specified input data for the geometric conditions, operational conditions, and radionuclide concentration conditions associated with the plants along the main flow channel of the river or estuary.

```
      DO 1100 IPLT=1,NPLT
      READ(5,1101)(PLNAME(IPLT,ID),ID=1,40),NPLPER(IPLT)
1101  FORMAT(10X,40A1,I4)
      READ(5,1102)IXINT(IPLT),DHBINT(IPLT),DHBBOT(IPLT),RGFINT(IPLT),
     1            CINCRW(IPLT),CINCRB(IPLT)
1102  FORMAT(6X,I4,1X,2(1X,E11.4),2X,F7.4,4X,2(1X,F7.4))
      READ(5,1103)IXDIS(IPLT),RGFDIS(IPLT),
     1            CDICRW(IPLT),CDICRB(IPLT)
1103  FORMAT(6X,I4,27X,F7.4,4X,2(1X,F7.4))
1100  CONTINUE
```

The specified input data for temporally constant conditions of the plants IPLT = 1, ..., NPLT located along the main flow channel consists of

PLNAME(IPLT,ID=1,40) = specified name (with a maximum of 40 letters) of plant IPLT located along the main flow channel (Sect. 6.13);

NPLPER(IPLT) = specified number of time periods for formulating the temporal variations (or temporally uniform conditions) of the operational conditions of plant IPLT located along the main flow channel (Sects. 4.8 and 6.13). At least one specified time period [i.e., NPLPER(IPLT) ⩾ 1] is required for specifying the temporal variations (or temporally uniform conditions) of the operational conditions and radionuclide concentration conditions associated with power plant IPLT located along the main flow channel;

IXINT(IPLT) = specified element containing the intake of plant IPLT along the curvilinear longitudinal *x*-axis of the main flow channel (Sects. 4.8 and 6.13);

DHBINT(IPLT) = specified, temporally constant depth of the intake of plant IPLT in the main flow channel (Sects. 4.8 and 6.13, ft);

DHBBOT(IPLT) = specified, temporally constant depth of the bottom of the main flow channel at the location of the intake of plant IPLT along the main flow channel (Sects. 4.8 and 6.13, ft);

RGFINT(IPLT) = specified constant factor for controlling the intake flow from the water layer for plant IPLT, representing the portion (as percentage) of the intake flow rate, withdrawn from the water layer, into the intake structure, in the element IXINT(IPLT), which contains the intake of plant IPLT [Eqs. (4.76), (4.87), and (4.88) and Sect. 6.13];

CINCRW(IPLT) = specified constant coefficient for controlling the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant IPLT, representing the factor required for determining the effect of the vertical

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location of the intake structure, relative to the water layer, on the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure, in the element IXINT(IPLT), which contains the intake of plant IPLT [Eqs. (4.77), (4.93a), and (4.93b) and Sect. 6.13];

CINCRB(IPLT) = specified constant coefficient for controlling bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant IPLT, representing the factor required for determining the effect of the vertical location of the intake structure, relative to the bottom layer, on the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure, in the element IXINT(IPLT), which contains the intake of plant IPLT [Eqs. (4.78) and (4.97) and Sect. 6.13];

IXDIS(IPLT) = specified element containing the discharge of plant IPLT along the curvilinear longitudinal *x*-axis of the main flow channel (Sects. 4.8 and 6.13);

RGFDIS(IPLT) = specified constant factor for controlling the discharge flow into the water layer for plant IPLT, representing the portion (as percentage) of the discharge flow rate, discharged into the water layer, from the discharge structure in the element IXDIS(IPLT), which contains the discharge of plant IPLT [Eqs. (4.79), (4.101), and (4.102) and Sect. 6.13];

CDICRW(IPLT) = specified constant coefficient for controlling water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant IPLT, representing the factor required for approximately considering the effects of the design and structural features of the discharge of plant IPLT on the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure, in the element IXDIS(IPLT), which contains the discharge of plant IPLT [Eqs. (4.80), (4.105), and (4.107) and Sect. 6.13];

CDICRB(IPLT) = specified constant coefficient for controlling bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant IPLT, representing the factor required for approximately considering the effects of the design and structural features of the discharge of plant IPLT on the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure, in the element IXDIS(IPLT), which contains the discharge of plant IPLT [Eqs. (4.81), (4.110), and (4.112) and Sect. 6.13].

```
      DO 1200 IPLT=1,NPLT
      NPER=NPLPER(IPLT)
      DO 1210 IPER=1,NPER
      READ(5,1211)IOPPER(IPLT,IPER),TPLPER(IPLT,IPER),
     1            GFLINT(IPLT,IPER),VLXINT(IPLT,IPER),
     2            JINCRW(IPLT,IPER),CRWINT(IPLT,IPER),
     3            JINCRB(IPLT,IPER),CRBINT(IPLT,IPER)
 1211 FORMAT(2X,I2,2X,3(1X,E11.4),2X,2(1X,I2,1X,E11.4))
      READ(5,1212)GFLDIS(IPLT,IPER),VLXDIS(IPLT,IPER),
     1            JDICRW(IPLT,IPER),CRWDIS(IPLT,IPER),
     2            JDICRB(IPLT,IPER),CRBDIS(IPLT,IPER)
 1212 FORMAT(18X,2(1X,E11.4),2X,2(1X,I2,1X,E11.4))
```

```
1210    CONTINUE
1200    CONTINUE
```

PLANTS reads the specified set of input data as IPER = 1, ..., NPER = NPLPER(IPLT) list of records for the durations of the specified time periods and the detailed information about the operational conditions and radionuclide concentration conditions associated with intake and discharge flows of all plants IPLT = 1, ..., NPLT along the main flow channel of a river or an estuary. This data set consists of

IOPPER(IPLT,IPER) = specified integer control parameter for operational conditions of plant IPLT during the specified time period TPLPER(IPLT,IPER) (Sects. 4.8 and 6.13);

= 0 as the user-specified option for indicating that plant IPLT is not operating during the specified time period TPLPER(IPLT,IPER);

= 1 as the user-specified option for indicating that plant IPLT is operating during the time period TPLPER(IPLT,IPER);

TPLPER(IPLT,IPER) = specified time period of the specified input data for operational conditions of plant IPLT, associated with intake and discharge flows of plant IPLT into or out of the main flow channel (Sects. 4.8 and 6.13, h);

GFLINT(IPLT,IPER) = specified intake flow rate of plant IPLT into or out of the main flow channel during the specified time period TPLPER(IPLT,IPER) (Sects. 4.8 and 6.13). If the user-specified value of the integer control parameter TOPPER(IPLT,IPER) = 0, which indicates that plant IPLT is not operating during the specified time period TPLPER(IPLT,IPER), the allocated space for the data record for the specified intake flow rate of plant IPLT can be left blank for the specified time period TPLPER(IPLT,IPER) (ft^3/h);

VLXINT(IPLT,IPER) = specified velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the intake flow of plant IPLT into or out of the main flow channel during the specified time period TPLPER(IPLT) (Sects. 4.8 and 6.13). If the input data record for velocity of the intake flow of plant IPLT is specified as zero (i.e., if the allocated space for the data record is left blank), the computational algorithm of PLANTS assumes that velocity of the intake flow of plant IPLT out of the main flow channel is equal either to velocity VLXIMX in the upstream half-element IMX = 2*IX − 1 or to velocity VLXIPX in the downstream half-element IPX = 2*IX, of the element IXPINT(IPLT), which contains the intake of plant IPLT (Sect. 6.13). Hence, if no information is available for specifying the value of velocity of plant IPLT out of the main flow channel, the data record for specified velocity of the intake flow of plant IPLT can be left blank for the flow out of the main flow channel, during the specified time period TPLPER(IPLT,IPER). Furthermore, if the user-specified value of the integer control parameter IOPPER(IPLT,IPER) = 0, which indicates that plant IPLT is not operating during the specified time period TPLPER(IPLT,IPER), the allocated space for the data record for the specified velocity of the intake flow of plant IPLT can be left blank for the specified time period TPLPER(IPLT) (ft/h);

JINCRW(IPLT,IPER) = specified value of the integer control parameter for determining the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eq. (4.89) and Sect. 6.13],

= 0 as the user-specified option for internally determining the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, based on (1) the water concentration of the radionuclide in the water layer CRW(IXRINT) in the element IXRINT = IXINT(IPLT), which contains the intake of plant IPLT, and (2) all available information about the local vertical variation of the water concentration of the radionuclide in the water layer and the vertical location of the structure of the intake of plant IPLT [Eqs. (4.89)–(4.93b) and Sect. 6.13];

= 1 as the user-specified option for directly specifying water concentration of the radionuclide in the intake flow, withdrawn from the water layer, based on specified input data for formulating temporal variations (or temporally uniform conditions) of water concentration of the radionuclide in the intake flow CRWINT(IPLT,IPER), withdrawn from the water layer, into the intake structure of plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.90) and (4.94) and Sect. 6.13];

CRWINT(IPLT,IPER) = specified conditions for water concentration of the radionuclide, associated with the intake flow of plant IPLT into or out of the main flow channel during the specified time period TPLPER(IPLT,IPER) [Eq. (4.90) and Sect. 6.13]. If no information is available for specifying the value of water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant IPLT, the data record for the specified water concentration of the radionuclide associated with the intake flow of plant IPLT out of the main flow channel can be left blank for the specified time period TPLPER(IPLT,IPER), by specifying the value of the integer control parameter for determining the water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant IPLT, as JINCRW(IPLT,IPER) = 0 for the specified time period TPLPER(IPLT,IPER). Furthermore, if the user-specified value of the integer control parameter IOPPER(IPLT,IPER) = 0, which indicates that plant IPLT has no effect on flow conditions and radionuclide concentration conditions in the main flow channel during the specified time period TPLPER(IPLT,IPER), the allocated space for the data record for specified water concentration of the radionuclide associated with the intake flow of plant IPLT can be left blank for the specified time period TPLPER(IPLT,IPER) (radiologic unit/ft^3);

JINCRB(IPLT,IPER) = specified value of the integer control parameter for determining the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eq. (4.95) and Sect. 6.13];

= 0 as the user-specified option for internally determining the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, based on (1) the bottom concentration of the radionuclide in the bottom layer CRB(IXRINT) in the element IXRINT = IXINT(IPLT), which contains the intake of plant IPLT, and (2) the specified value of constant coefficient CINCRB(IPLT) for controlling bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant IPLT [Eqs. (4.78) and (4.97) and Sect. 6.13],

= 1 as the user-specified option for directly specifying bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, based on specified input data for formulating temporal variations (or temporally uniform conditions) of bottom concentration of the radionuclide in the intake flow CRBINT(IPLT,IPER), withdrawn from the bottom layer, into the intake structure of plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.96) and (4.98) and Sect. 6.13];

CRBINT(IPLT,IPER) = specified conditions for bottom concentration of the radionuclide, associated with the intake flow of plant IPLT into or out of the main flow channel during the specified time period TPLPER(IPLT,IPER) [Eq. (4.96) and Sect. 6.13]. If no information is available for specifying the value of bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant IPLT, the data record for the specified bottom concentration of the radionuclide associated with the intake flow of plant IPLT out of the main flow channel can be left blank for the specified time period TPLPER(IPLT,IPER), by specifying the value of the integer control parameter for determining the bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant IPLT, as JINCRB(IPLT,IPER) = 0 for the specified time period TPLPER(IPLT,IPER). Furthermore, if the user-specified value of the integer control parameter IOPPER(IPLT,IPER) = 0, which indicates that plant IPLT has no effect on flow conditions and radionuclide concentration conditions in the main flow channel during the specified time period TPLPER(IPLT,IPER), the allocated space for the data record for specified bottom concentration of the radionuclide associated with the intake flow of plant IPLT can be left blank for the specified time period TPLPER(IPLT,IPER) (radiologic unit/ft^3);

GFLDIS(IPLT,IPER) = specified discharge flow rate of plant IPLT into the main flow channel during the specified time period TPLPER(IPLT,IPER) (Sects. 4.8 and 6.13). If the user-specified value of the integer control parameter IOPPER(IPLT,IPER) = 0, which indicates that plant IPLT is not operating during the time period TPLPER(IPLT,IPER), the allocated space for the data record for the specified discharge flow rate of plant IPLT can be left blank for the specified time period TPLPER(IPLT,IPER) (ft^3/h);

VLXDIS(IPLT,IPER) = specified velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) of the discharge flow of plant IPLT into the main flow channel during the specified time period TPLPER(IPLT) (Sects. 4.8 and 6.13). If the input data record for velocity of the discharge flow of plant IPLT is specified as zero (i.e., if the allocated space for the data record is left blank), the computational algorithm of PLANTS assumes the discharge flow of plant IPLT is normal to the curvilinear longitudinal *x*-axis of the main flow channel. Therefore, it assumes that the discharge flow of plant IPLT does not have any momentum along the curvilinear longitudinal *x*-axis of the main flow channel. Hence, if information about the direction of the discharge structure of plant IPLT is not available, the user can leave the input data record for velocity of the discharge flow of plant IPLT blank, indicating that momentum of the discharge flow of plant IPLT along the curvilinear longitudinal *x*-axis of the main flow channel is negligible. Furthermore, if the user-specified value of the integer control parameter IOPPER(IPLT,IPER) = 0, which indicates that plant IPLT is not operating during the specified time period TPLPER(IPLT,IPER), the space allocated for the data record for the specified velocity of the discharge flow of plant IPLT can be left blank for the specified time period TPLPER(IPLT) (ft/h);

JDICRW(IPLT,IPER) = specified value of the integer control parameter for determining water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.103), (4.104), and (4.106) and Sect. 6.13];

= 0 as the user-specified option for internally determining water concentration of the radionuclide in the discharge flow, discharged into the water layer, based on (1) CRWINX as the already calculated water concentration of the radionuclide in the intake flow, withdrawn from the water layer, into the intake structure of plant IPLT, (2) CDICRW(IPLT) as the specified temporally constant coefficient for controlling the water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant IPLT, representing the factor required for approximately considering the effects of the design and structural features of the discharge of plant IPLT, and (3) the specified radionuclide concentration rise CRWDPL(IPLT) = CRWDIS(IPLT,IPER), as the specified input data for CRWDIS(IPLT,IPER) which represents the additional radionuclide release, into the circulating water system, discharged into the water layer, that occurs in plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.103), (4.104), and (4.105) and Sect. 6.13];

= 1 as the user-specified option for directly specifying water concentration of the radionuclide in the discharge flow, discharged into the water layer, based on specified input data for formulating temporal variations (or temporally uniform conditions) of water concentration of the radionuclide in the discharge flow CRWDIS(IPLT,IPER), discharged into the water layer, from the discharge structure of plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.103), (4.106), and (4.107) and Sect. 6.13];

CRWDIS(IPLT,IPER) = specified conditions for water concentration of the radionuclide associated with the discharge flow of plant IPLT into the main flow channel during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.104) and (4.106) and Sect. 6.13], according to one of the two user-specified options:

1. For the specified value of the integer control parameter JDICRW(IPLT,IPER) = 0, which indicates the user-specified option for internally determining water concentration of the radionuclide in the discharge flow, discharged into the water layer, based on the radionuclide concentration rise in the plant IPLT, the specified input data must be for radionuclide concentration rise that occurs in the plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eq. (4.104) and Sect. 6.13];
2. For the specified value of the integer control parameter JDICRW(IPLT,IPER) = 1, which indicates the user-specified option for directly specifying water concentration of the radionuclide in the discharge flow, discharged into the water layer, the specified input data must be for water concentration of the radionuclide in the discharge flow, discharged into the water layer, from the discharge structure of plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eq. (4.106) and Sect. 6.13];

Again, if the user-specified value of the integer control parameter IOPPER(IPLT,IPER) = 0, which indicates that plant IPLT has no effect on flow conditions and radionuclide concentration conditions in the main flow channel during the specified time period TPLPER(IPLT,IPER), the allocated space for the data record for specified conditions for water concentration of the radionuclide associated with the discharge flow of plant IPLT can be left blank for the specified time period TPLPER(IPLT,IPER) (radiologic unit/ft^3);

JDICRB(IPLT,IPER) = specified value of the integer control parameter for determining bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.108), (4.109), and (4.111) and Sect. 6.13];

= 0 as the user-specified option for internally determining bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, based on (1) CRBINX as the already calculated bottom concentration of the radionuclide in the intake flow, withdrawn from the bottom layer, into the intake structure of plant IPLT, (2) CDICRB(IPLT) as the specified temporally constant coefficient for controlling the bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant IPLT, representing the factor required for approximately considering the effects of the design and structural features of the discharge of plant IPLT, and (3) the specified radionuclide concentration rise CRBDPL(IPLT = CRBDIS(IPLT,IPER), as the specified input data for CRBDIS(IPLT,IPER) which represents the additional radionuclide release, into the circulating water system, discharged into the bottom layer, that occurs in plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.108), (4.109), and (4.110) and Sect. 6.13].

= 1 as the user-specified option for directly specifying bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, based on specified input data for formulating temporal variations (or temporally uniform conditions) of bottom concentration of the radionuclide in the discharge flow CRBDIS(IPLT,IPER), discharged into the bottom layer, from the discharge structure of plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.108), (4.111), and (4.112) and Sect. 6.13];

CRBDIS(IPLT,IPER) = specified conditions for bottom concentration of the radionuclide associated with the discharge flow of plant IPLT into the main flow channel during the specified time period TPLPER(IPLT,IPER) [Eqs. (4.109) and (4.111) and Sect. 6.13], according to one of the two user-specified options:

1. For the specified value of the integer control parameter JDICRB(IPLT,IPER) = 0, which indicates the user-specified option for internally determining bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, based on the radionuclide concentration rise in the plant IPLT, the specified input data must be for radionuclide concentration rise that occurs in the plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eq. (4.109) and Sect. 6.13];
2. For the specified value of the integer control parameter JDICRB(IPLT,IPER) = 1, which indicates the user-specified option for directly specifying bottom concentration of

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the radionuclide in the discharge flow, discharged into the bottom layer, the specified input data must be for bottom concentration of the radionuclide in the discharge flow, discharged into the bottom layer, from the discharge structure of plant IPLT, during the specified time period TPLPER(IPLT,IPER) [Eq. (4.111) and Sect. 6.13];

Again, if the user-specified value of the integer control parameter IOPPER(IPLT,IPER) = 0, which indicates that plant IPLT has not effect on flow conditions and radionuclide concentration conditions in the main flow channel during the specified time period TPLPER(IPLT,IPER), the allocated space for the data record for specified conditions for bottom concentration of the radionuclide associated with the discharge flow of plant IPLT can be left blank for the specified time period TPLPER(IPLT,IPER) (radiologic unit/ft^3).

It is important to note that, for computer simulations that do not require detailed information about temporal variations of the operational conditions and radionuclide concentration conditions of plants along the main flow channel, the user can implement the RADONE computer code with simplified specified input data for the operational conditions and radionuclide concentration conditions of any plant IPLT, with a single-record specified input data set, with IPER = NPLPER(IPLT) = 1, which would be sufficient for representing the approximately temporally uniform operational conditions and radionuclide concentration conditions of the plant IPLT associated with intake and discharge flows into (or out of) the main flow channel.

7.13 SPECIFIED INPUT DATA FOR THE MODULAR SUBROUTINE RADIOR

The modular subroutine RADIOR reads the required set of specified input data, from the input device designated by the logical unit selected by the user, for formulating (1) the first-order radiological decay effect of the radionuclide in the water layer [Eq. (3.12a)] and (2) the first-order radiological decay effect of the radionuclide in the bottom layer [Eq. (3.12b)] in the main flow channel (Sect. 6.14).

```
      READ(5,1001))RADNAM(ID),ID=1,16),THRHLF
1001  FORMAT(10X,16A1,4X,E11.4)
```

RADNAM(ID=1,16) = specified indentification information for the radionuclide (maximum of 16 characters);

THRHLF = specified half-life of the radionuclide [Eq. (3.93)].

The specified input data for the first-order radiological decay effects require the specification of the half-life of the radionuclide rather than the nuclear decay rate coefficient [Eqs. (3.92a), (3.92b), and (3.93)] for reasons of convenience to the user. The appropriate value of the first-order nuclear decay rate coefficient is calculated internally in the modular subroutine RADIOR [Eq. (3.93) and Sect. 6.14].

7.14 DISCUSSION OF THE STORAGE REQUIREMENTS FOR THE INPUT DATA

The advanced development program version of the RADONE computer code stores most of the specified input data required by the modular and auxiliary subroutines. All important sets of specified input data for

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the temporal variations are stored to enable the user to check the input data before implementing the code for long-term simulations of flow conditions and radionuclide concentration conditions in a river or an estuary. The RADONE computer code was specifically designed for applications to site-specific problems for the assessment of the radiologic impact on the receiving water body that would result from accidental radiological release scenarios that could occur in the geographic region of the main flow channel of a controlled-flow river or a tidal estuary. Therefore, the RADONE computer code includes all the necessary capabilities for incorporating detailed information about the flow conditions and radionuclide concentration conditions in the geographic region which can effect the flow conditions and radionuclide concentration conditions in the main flow channel of a river or an estuary. It can incorporate large sets of specified input data incorporating detailed information about the end conditions, stream or tributary flow conditions, climatological conditions, and plant operational conditions. Hence, in certain applications of the RADONE computer code to the simulation of detailed flow conditions and radionuclide concentration conditions in the main flow channel of a river or an estuary, it is extremely important that no error is contained in any of the extensive sets of specified input data to the modular and auxiliary subroutines. The advanced development program version of the RADONE computer code includes the option to print out all sets of specified input data for all the modular and auxiliary subroutines, before starting the long-term simulations, so that the user can check the stored sets of specified input data for possible errors (Sect. 8). Because an error in any important set of specified input data for any modular or auxiliary subroutine would cause errors in the numerical solutions of flow conditions and radionuclide concentration conditions in the river or estuary, the user is strongly advised to use this option for checking all sets of specified input data for the modular and auxiliary subroutines before attempting any long-term computer simulations with the RADONE computer code.

The present advanced development program version of the RADONE computer code does not include the capability for dynamic dimensioning of storage allocations for the sets of specified input data for the modular and auxiliary subroutines. Hence, the user is required to change the dimensions for all COMMON and DIMENSION statements in all the modular and auxiliary subroutines, depending on the sets of specified input data that would be used in the application of the RADONE computer code to the simulation of flow conditions in a river or an estuary. It is important that the user carefully consider the dimensions of each COMMON or DIMENSION statement associated with a particular set of stored specified input data in each modular or auxiliary subroutine. The user is advised not to overdimension any of the COMMON or DIMENSION statements in any modular or auxiliary subroutine, because unused large storage allocations for the specified input data would increase the computer processing unit (CPU) time and cost of the computer simulations, particularly in computer systems operating in a time-sharing mode.

Furthermore, for long-term and accurate simulations of flow conditions and radionuclide concentration conditions in an actual controlled river or a tidal estuary with detailed and accurate temporal variations of end conditions, stream or tributary flow conditions, climatological conditions, and plant operational conditions the sets of specified input data for the modular and auxiliary subroutines could require extensive storage that could result in increased CPU time and cost for the computer runs of the RADONE computer code. In such cases, the user is strongly advised to consider the following two operational characteristics of the RADONE computer code:

1. All modular subroutines of the RADONE computer code are designed to operate with simplified sets of specified input data that would require minimum amounts of storage allocations as well as extensive sets of specified input data, which would require large amounts of storage allocations. Hence, based on careful considerations of anticipated flow conditions and radionuclide concentration conditions in a

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river or an estuary, the user should first decide about the level of accuracy that would be required in the calculations of each modular subroutine. The modular subroutines that do not require high levels of accuracy in their calculations should be supplied with simplified sets of specified input data, which would require only minimum amounts of storage allocations. Only the modular subroutines that require high levels of accuracy in their calculations should be supplied with extensive sets of specified input data, which could require large amounts of storage allocations. The user is advised to use simplified sets of specified input data to the modular subroutines unless it is absolutely necessary to consider extensive sets of specified input data for simulating very accurate and detailed flow conditions and radionuclide concentration conditions in a river or an estuary.

2. The RADONE computer code includes the necessary capability to stop and restart the calculations at any time during the computer simulations. Hence, a required long-term simulation with an overall, relatively long duration can be readily divided into a number of successive short-term simulations with relatively shorter durations. The required amounts of storage allocations for the sets of specified input data for each short-term simulation, with relatively shorter duration, would automatically become much less than the amount of storage allocations that would be required for the complete sets of specified input data for the long-term simulations, because each data set of specified input data for each short-term simulation would be only a part of the complete set of specified input data for the long-term simulation. Hence, the user is also advised to consider successive short-term simulations, with relatively short durations, in obtaining the computer simulation results for a required long-term simulation with a relatively long duration, by stopping and restarting the calculations, based on the restart capability of the RADONE computer code according to the special features of the modular subroutine OUTPUT (Sect. 6.15) and the modular subroutine INITAL (Sects. 6.4 and 7.4).

The production program version of the RADONE computer code can completely eliminate the storage requirement for the sets of specified input data for the modular subroutines. However, because it also eliminates the important capability of the currently available advanced development program version in printing out all of the sets of specified input data for the modular subroutines before starting the long-term computer simulations, it is recommended that the user not utilize the production program version of the RADONE computer code unless it is required to obtain numerous sets of computer simulation results for a large number of different accidental radiological release scenarios for plant operational conditions with the same sets of specified input data for end conditions, stream or tributary flow conditions, and climatological conditions for a controlled-flow river or a tidal estuary.

8. OUTPUT OF THE RADONE COMPUTER CODE

The present "advanced development program" version of the RADONE computer code includes ten modular subroutines (REGION, ENDCON, TURBUL, GROUND, BOTTOM, SURFAC, STREAM, PLANTS, RADIOR, and OUTPUT) and the auxiliary subroutine STORER, which produce output with different formats according to user-specified options.

8.1 GENERAL DISCUSSION OF OUTPUT FORMATS

The structure of the RADONE computer code is designed to make available to the user four different kinds of output, consisting of

1. printed output of all sets of specified input data for the various modular subroutines,
2. printed output of the results of the computer simulations for flow conditions and radionuclide concentration conditions in the main flow channel,
3. output for the set of specified input data for the principal solution variables for restarting the subsequent computer simulations, and
4. special auxiliary output for storing the results of the computer simulations.

The modular and auxiliary subroutines of the RADONE computer code write the four different kinds of output on any number of different output devices, designated by the different logical units selected by the user (Table 8.1).

According to the compilers of the Digital Equipment Corporation (DEC) computer systems, output from the different subroutines would be written directly on the different specified output devices designated by the different logical unit numbers. In executing the RADONE computer code in other computer systems [e.g., IBM and Control Data Corporation (CDC)], special control instructions may be needed to establish the correct order of output from the different modular subroutines (Table 8.1).

The RADONE computer code includes three integer control parameters that are read in the MAIN program and passed through the labeled COMMON/PUTOUT/. These parameters specify the kind of output required from the different modular and auxiliary subroutines, according to the user-specified options (Sect. 7.2).

Table 8.1. Writing order and logical unit numbers of the output devices for the modular and auxiliary subroutines of the RADONE computer code

Writing order of output files	Subroutine	Logical unit number of selected output device
1	REGION	user-selectable or (6)
2	ENDCON	user-selectable or (6)
3	TURBUL	user-selectable or (6)
4	BOTTOM	user-selectable or (6)
5	GROUND	user-selectable or (6)
6	SURFAC	user-selectable or (6)
7	STREAM	user-selectable or (6)
8	PLANTS	user-selectable or (6)
9	RADIOR	user-selectable or (6)
10	OUTPUT	user-selectable or (6,7)
11	STORER	user-selectable or (6)

IWDATA = the specified integer control parameter as the user-specified option for including or excluding the printed output of all required sets of specified input data read by all the modular and auxiliary subroutines;

= 0 as the user-specified option for excluding the printed output;
= 1 as the user-specified option for including the printed output.

IWRITE = the specified integer control parameter as the user-specified option for including or excluding the detailed printed output of the computer results for all principal solution variables of the solution by the modular subroutine OUTPUT (Sect. 6.15);

= 0 as the user-specified option for excluding the detailed printed output;
= 1 as the user-specified option for including the detailed printed output.

ISTORE = the specified integer control parameter as the user-specified option for including or excluding the special abbreviated form of output by the auxiliary subroutine STORER (Sect. 6.16) for the set of computed results for the auxiliary computer graphics programs and for special applications with hourly variations of the hydrodynamic conditions that can be used as the required specified input data for the auxiliary subroutine FLOWER (Sect. 6.17);

= 0 as the user-specified option for excluding the special abbreviated form of output by the auxiliary subroutine STORER (Sect. 6.16), which is not utilized;
= 1 as the user-specified option for including the special abbreviated form of output by the auxiliary subroutine STORER (Sect. 6.16). STORER is called in the intermediate output stage of the modular subroutine OUTPUT at every intermediate output time level (Sect. 6.15).

In applications of the RADONE computer code to the simulation of detailed flow conditions and radionuclide concentration conditions in a controlled river or a tidal estuary, it is very important that the user correctly prepare all required sets of specified input data for the modular subroutines. Hence, the user is advised to consider the special case with IWDATA = 1 for trial runs of the RADONE computer code, which will generate detailed printed output of all required sets of specified input data for the modular subroutines before attempting the long-term computer simulations of flow conditions and radionuclide concentration conditions in the main flow channel of a controlled river or a tidal estuary.

Subsequent sections present discussions of the kinds of output generated by the ten modular subroutines (REGION, ENDCON, TURBUL, BOTTOM, GROUND, SURFAC, STREAM, PLANTS, RADIOR, and OUTPUT) and the auxiliary subroutine STORER, according to the user-specified options, IWDATA, IWRITE, and ISTORE, of the RADONE computer code.

8.2 DISCUSSIONS OF OUTPUT OF THE MODULAR SUBROUTINE REGION

The modular subroutine REGION writes, as printed output, on the output device designated by the logical unit selected by the user, only for the specified value of the integer control parameter IWDATA = 1, which indicates the user-specified option for including the printed output of all required sets of specified input data read by the modular and auxiliary subroutines. The output of REGION consists of the rearranged and modified forms of the specified input data for the detailed geometric characteristics of the cross sections of the main flow channel of the river or estuary (Sects. 6.3 and 7.3).

8.3 DISCUSSIONS OF OUTPUT OF THE MODULAR SUBROUTINE ENDCON

The modular subroutine ENDCON writes, as printed output, on the output device designated by the logical unit selected by the user, only for the specified value of the integer control parameter IWDATA = 1, which indicates the user-specified option for including the printed output of all required sets of specified input data read by the modular and auxiliary subroutines. The output of ENDCON consists of the rearranged and modified forms of the specified input data for the three different user-specified cases of conditions at the upstream end and/or at the downstream end of the main flow channel.

For the specified values of the integer control parameters IUPCON = 0 and/or IDNCON = 0, which indicate the user-specified cases for simple closed-dam conditions at the upstream end and/or the downstream end of the main flow channel, ENDCON prints out only a simple output indicating simple closed-dam conditions.

For the specified values of the integer control parameters IUPCON = 1 and/or IDNCON = 1, which indicate the user-specified cases for controlled-flow dam conditions at the upstream end and/or downstream end of the main flow channel, ENDCON prints out detailed output of the sets of specified input data for the temporal variations, according to specified time periods, of flow conditions and radionuclide concentration conditions at the upstream end and/or downstream end of the main flow channel (Sects. 6.6 and 7.6).

For the specified values of the integer control parameters IUPCON = 2 and/or IDNCON = 2, which indicate the user-specified cases for tidal flow conditions at the upstream end and/or downstream end of the main flow channel, ENDCON prints out detailed output of the sets of specified input data for (1) the short-term temporal variations of flow conditions and radionuclide concentration conditions, based on the tidal harmonics, and (2) the long-term temporal variations of flow conditions and radionuclide concentration conditions, according to specified time periods at the upstream end and/or the downstream end of the main flow channel (Sects. 6.6 and 7.6).

8.4 DISCUSSIONS OF OUTPUT OF THE MODULAR SUBROUTINE TURBUL

The modular subroutine TURBUL writes, as printed output, on the output device designated by the logical unit selected by the user, only for the specified value of the integer control parameter IWDATA = 1, which indicates the user-specified option for including the printed output of all required sets of specified input data read by the modular and auxiliary subroutines. The output of TURBUL consists of the rearranged and modified forms of the specified input data for calculations of nonconvective transport rates (convection-defect transport rates and eddy-turbulent transport rates, along the curvilinear longitudinal x-axis of the main flow channel) (Sects. 6.8 and 7.7).

8.5 DISCUSSIONS OF OUTPUT OF THE MODULAR SUBROUTINE BOTTOM

The modular subroutine BOTTOM writes, as printed output, on the output device designated by the logical unit selected by the user, only for the specified value of the integer control parameter IWDATA = 1, which indicates the user-specified option for including the printed output of all required sets of specified input data read by the modular and auxiliary subroutines. The output of BOTTOM consists of the rearranged and modified forms of the specified input data for calculations of bottom radionuclide transport rates between the water layer and the bottom layer in the main flow channel (Sects. 6.10 and 7.9).

8.6 DISCUSSIONS OF OUTPUT OF THE MODULAR SUBROUTINE GROUND

The modular subroutine GROUND writes, as printed output, on the output device designated by the logical unit selected by the user, only for the specified value of the integer control parameter IWDATA = 1, which indicates the user-specified option for including the printed output of all required sets of specified input data read by the modular and auxiliary subroutines. The output of GROUND consists of the rearranged and modified forms of specified input data for the two parts of groundwater seepage flow conditions and radionuclide concentration conditions into or out of the main flow channel (Sects. 6.9 and 7.8).

GROUND first prints out the specified input data for the temporally constant geophysical conditions of the bed of the main flow channel in the geographic (climatological) region of the river or estuary that control groundwater seepage flow conditions into or out of the elements IX = 1, ..., NX of the main flow channel (Sects. 3.6, 4.6, 6.9, and 7.8).

GROUND also prints out the specified input data for the spatially averaged conditions that approximately represent the temporal variations, according to specified time periods, of the geophysical conditions in the geographic (climatological) region of the river or estuary that control groundwater seepage flow conditions and radionuclide concentration conditions into or out of the main flow channel (Sects. 3.6, 4.6, 6.9, and 7.8).

8.7 DISCUSSIONS OF OUTPUT OF THE MODULAR SUBROUTINE SURFAC

The modular subroutine SURFAC writes, as printed output, on the output device designated by the logical unit selected by the user, only for the specified value of the integer control parameter IWDATA = 1, which indicates the user-specified option for including the printed output of all required sets of specified input data read by the modular and auxiliary subroutines. The output of SURFAC consists of the rearranged and modified forms of the specified input data for the two parts of the climatological conditions and radionuclide concentration conditions in the geographic (climatological) region of the river or estuary that control transport conditions at the water surface of the main flow channel (Sects. 3.7, 4.5, 6.11 and 7.10).

SURFAC first prints out the specified input data for the temporally constant geometric conditions, which consist of the orientation of the curvilinear longitudinal direction of the main flow channel and the drainage areas associated with the elements IX = 1, ..., NX of the main flow channel (Sects. 4.5, 6.11, and 7.10).

SURFAC also prints out specified input data for the spatially averaged, detailed temporal variations of climatological conditions and radionuclide concentration conditions, including (1) the long-term variations, based on specified time periods, and (2) the short-term hourly variations, within 1 d, based on two cosine harmonics, in the geographic (climatological) region of the main flow channel (Sects. 4.5, 6.11, and 7.10).

8.8 DISCUSSIONS OF OUTPUT OF THE MODULAR SUBROUTINE STREAM

The modular subroutine STREAM writes, as printed output, on the output device designated by the logical unit selected by the user, only for the specified value of the integer control parameter IWDATA = 1, which indicates the user-specified option for including the printed output of all required sets of specified input data read by the modular and auxiliary subroutines. The output of STREAM consists of the rearranged and modified forms of specified input data for the two parts of the flow conditions and

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radionuclide concentration conditions associated with streams or tributaries flowing into or out of the main flow channel (Sects. 4.7, 6.12, and 7.11).

STREAM first prints out the specified input data for the temporally constant conditions. This data set consists of

1. locations of the connecting junctions along the curvilinear longitudinal *x*-axis of the main flow channel and
2. control conditions associated with the flow of streams or tributaries ISRM = 1, .., NSRM flowing into or out of the main flow channel (Sects. 4.7, 6.12, and 7.11).

STREAM also prints out the specified input data for the detailed temporal variations, based on specified time periods, of flow conditions and radionuclide concentration conditions associated with streams or tributaries flowing into or out of the main flow channel (Sects. 4.7, 6.12, and 7.11).

8.9 DISCUSSIONS OF OUTPUT OF THE MODULAR SUBROUTINE PLANTS

The modular subroutine PLANTS writes, as printed output, on the output device designated by the logical unit selected by the user, only for the specified value of the integer control parameter IWDATA = 1, which indicates the user-specified option for including the printed output of all required sets of specified input data read by the modular and auxiliary subroutines. The output of PLANTS consists of the rearranged and modified forms of the specified input data for the two parts of the operational conditions of plants that determine the flow conditions and radionuclide concentration conditions of the intake and/or discharge flows into or out of the main flow channel (Sects. 4.8, 6.13, and 7.12).

PLANTS firsts prints out the specified input data for the temporally constant conditions. This data set consists of

1. locations of the intakes and/or discharges of plants along the curvilinear longitudinal *x*-axis of the main flow channel and
2. control conditions associated with intake and/or discharge flows of the plants IPLT = 1, ..., NPLT into or out of the main flow channel (Sects. 4.8, 6.13, and 7.12).

PLANTS also prints out the specified input data for the detailed temporal variations, based on specified time periods, of the operational conditions of the plants that control the flow conditions and radionuclide concentration conditions of intake and/or discharge flows of the plants into or out of the main flow channel (Sects. 4.8, 6.13, and 7.12).

8.10 DISCUSSIONS OF OUTPUT OF THE MODULAR SUBROUTINE RADIOR

The modular subroutine RADIOR writes, as printed output, on the output device designated by the logical unit selected by the user, only for the specified value of the integer control parameter IWDATA = 1, which indicates the user-specified option for including the printed output of all required sets of specified input data read by the modular and auxiliary subroutines. The output of RADIOR consists of the rearranged and modified forms of the specified input data for calculations of first-order radiological decay rate for the water layer and first-order radiological decay rate for the bottom layer in the main flow channel (Sects. 3.8 and 6.14).

8.11 DISCUSSIONS OF OUTPUT OF THE MODULAR SUBROUTINE OUTPUT

The modular subroutine OUTPUT coordinates all the different outputs, with different output formats and different output devices, associated with the computer simulation results of the RADONE computer code for the principal solution variables of the radionuclide transport model (Sects. 2 and 5). OUTPUT directly writes all regular printed output for the results of the principal solution variables, and it calls the auxiliary subroutine STORER, which writes the computed results of the principal solution variables according to special output formats for storing the information or for use in auxiliary computer graphics programs.

The internally written, regular printed output of OUTPUT consists of two parts: (1) the output of the principal solution variables at every intermediate output time level T after every NTW computational time step and (2) the output of the restart file, according to the exact format of the specified input data for the modular subroutine INITAL (Sects. 6.4 and 7.4), for the last time level T after NT computational time steps, which represent the end of the specified period of the computer simulations.

OUTPUT writes, as printed output, on the output device designated by the logical unit selected by the user, only for the specified value of the integer control parameter IWRITE = 1, which indicates the user-specified option for including the detailed regular printed output of the results of the computer simulations for the principal solution variables in all elements IX = 1, ..., NX of the main flow channel, at every intermediate output time level T, after every NTW computational time step.

```
      WRITE(6,2001)T,NDAY,THRDAY
2001  FORMAT(1H1,34X,15H***** TIME, T =,E13.6,8H HOURS (,I4,5H DAYS,
     1 F8.2,13H HOURS) *****)
```

T = intermediate output time level at the end of every NTW time step (Sect. 6.15), representing the time since the start of the computer simulations (h);

NDAY = number of completed days corresponding to the intermediate output time level T at the end of every NTW time step (Sect. 6.15), representing the number of completed days since the start of the computer simulations (d);

THRDAY = hour of the day after NDAY number of completed days, corresponding to the intermediate output time level T at the end of every NTW time step (Sect. 6.15) (hour of the day).

```
      WRITE(6,2005)UPSIMH,XC(1),DHSRMW,DHBUPS,VFSUPS,GFSUPS,CRWUPS,
     1              CRBUPS
2005  FORMAT(1HO,F5.1,1X,E11.4,2(1X,E11.4),1X,E11.4,1X,
     1            13X,E11.4,26X,2(1X,E11.4))
```

UPSIMH = 0.5, designating the upstream-end enclosure surface of the main flow channel;

XC(1) = location (along the curvilinear longitudinal *x*-axis of the main flow channel) of the upstream-end enclosure surface of the main flow channel (ft);

DHSRMW = difference between (1) the water surface elevation HSRUPS at the upstream-end enclosure surface of the main flow channel and (2) HSRMWL as the representative mean water level for the total length TXLEST of the main flow channel (Sects. 6.6 and 6.15) (ft);

DHBUPS = HSC(1) depth at the upstream-end enclosure surface of the main flow channel (ft);

VFSUPS = converted value of channel flow velocity (along the curvilinear longitudinal x-axis of the main flow channel) at the upstream-end enclosure surface of the main flow channel (ft/s);

GFSUPS = converted value of channel flow rate (along the curvilinear longitudinal x-axis of the main flow channel) at the upstream-end enclosure surface of the main flow channel (ft^3/s);

CRWUPS = water concentration of the radionuclide in the water layer at the upstream-end enclosure surface of the main flow channel (radiologic unit/ft^3);

CRBUPS = bottom concentration of the radionuclide in the bottom layer at the upstream-end enclosure surface of the main flow channel (radiologic unit/ft^3).

```
      DO 2010 IX=1,NX
      •
      •
      •
      WRITE(6,2011)IX,X(IX),DHSRMW,DHBIII,VFSIII,GFSIMX,GFSIII,GFSIPX,
     1             CRW(IX),CRB(IX)
 2011 FORMAT(1H ,1X,I3,2X,E11.4,2(1X,E11.4),1X,E11.4,1X,
     1        3(1X,E11.4),2X,2(1X,E11.4))
 2010 CONTINUE
```

IX = integer designating the element;

X(IX) = location (along the curvilinear longitudinal x-axis of the main flow channel) of the element IX (ft);

DHSRMW = difference between (1) water surface elevation HSR(IX) in the element IX and (2) HSRMWL as the representative mean water level for the total length TXLEST of the main flow channel (Sects. 6.6 and 6.15) (ft);

DHBIII = calculated (interpolated) depth in the element IX (ft);

VFSIII = converted value of channel flow velocity (along the curvilinear longitudinal x-axis of the main flow channel) in the element IX (ft/s);

GFSIMX = converted value of channel flow rate (along the curvilinear longitudinal x-axis of the main flow channel) in the upstream half-element IMX = 2*IX − 1 (ft^3/s);

GFSIII = converted value (interpolated) of channel flow rate in the element IX (ft^3/s);

GFSIPX = converted value of channel flow rate in the downstream half-element IPX = 2*IX (ft^3/s);

CRW(IX) = water concentration of the radionuclide in the water layer in the element IX (radiologic unit/ft^3);

CRB(IX) = bottom concentration of the radionuclide in the bottom layer in the element IX (radiologic unit/ft^3).

```
      WRITE(6,2006)DNSIPH,XC(NC),DHSRMW,DHBDNS,VFSDNS,GFSDNS,CRWDNS,
     1              CRBDNS
 2006 FORMAT(1H ,F5.1,1X,E11.4,2(1X,E11.4),1X,E11.4,1X,
     1           13X,E11.4,26X,2(1X,E11.4))
```

DNSIPH = NX + 0.5, designating the downstream-end enclosure surface of the main flow channel;

XC(NC) = location (along the curvilinear longitudinal *x*-axis of the main flow channel) of the downstream-end enclosure surface of the main flow channel (ft);

DHSRMW = difference between (1) the water surface elevation HSRDNS at the downstream-end enclosure surface of the main flow channel and (2) HSRMWL as the representative mean water level for the total length TXLEST of the main flow channel (Sects. 6.6 and 6.15) (ft);

DHBDNS = HSC(NC) depth at the downstream-end enclosure surface of the main flow channel (ft);

VFSDNS = converted value of channel flow velocity (along the curvilinear longitudinal *x*-axis of the main flow channel) at the downstream-end enclosure surface of the main flow channel (ft/s);

GFSDNS = converted value of channel flow rate (along the curvilinear longitudinal *x*-axis of the main flow channel) at the downstream-end enclosure surface of the main flow channel (ft^3/s);

CRWDNS = water concentration of the radionuclide in the water layer at the downstream-end enclosure surface of the main flow channel (radiologic unit/ft^3);

CRBDNS = bottom concentration of the radionuclide in the bottom layer at the downstream-end enclosure surface of the main flow channel (radiologic unit/ft^3).

```
      WRITE(6,2101)HSRERR
 2101 FORMAT(1H0,20X,70H**** MAXIMUM ABSOLUTE TRUNCATION ERROR FOR SURFA
     1CE ELEVATION, HSRERR =,E13.6)
      WRITE(6,2102)GFXERR
 2102 FORMAT(1H ,20X,70H**** MAXIMUM ABSOLUTE TRUNCATION ERROR FOR FLOW
     1RATE,           GFXERR =,E13.6)
      WRITE(6,2103)CRWERR
 2103 FORMAT(1H ,20X,70H**** MAXIMUM ABSOLUTE TRUNCATION ERROR FOR CRW C
     1ONCENTRATION, CRWERR =,E13.6)
      WRITE(6,2104)CRBERR
 2104 FORMAT(1H ,20X,70H**** MAXIMUM ABSOLUTE TRUNCATION ERROR FOR CRB C
     1ONCENTRATION, CRBERR =,E13.6)
```

The values of the absolute norms of the truncation errors associated with the numerical integration of the discrete-element equations by the Runge-Kutta-Gill method (Sect. 5) for the solution of the principal solution variables consist of

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HSRERR = absolute norm of the truncation error for water surface elevation (ft);

GFXERR = absolute norm of the truncation error for channel flow rate (along the curvilinear longitudinal *x*-axis of the main flow channel) (ft/h);

CRWERR = absolute norm of the truncation error for water concentration of the radionuclide in the water layer (radiologic unit/ft^3);

CRBERR = absolute norm of the truncation error for bottom concentration of the radionuclide in the bottom layer (radiologic unit/ft^3).

It is important to note that the absolute norms of the truncation errors are strictly related to the numerical integration by the Runge-Kutta-Gill method. The printed output results for absolute norms of the truncation errors do not directly indicate the stability (or instability) characteristics of the solutions of the governing system of discrete-element equations (Sect. 5.3). However, during the computer simulations, if any absolute norm of the truncation error associated with the numerical integration of the discrete-element equation for the solution of a principal solution variable tends to grow continuously, it generally corresponds to the start of the unstable behavior of the solutions of the governing system of discrete-element equations.

At the last time level T of the computations, after NT time steps, OUTPUT writes, on the output device designated by the logical unit selected by the user, the restart file, according to the exact format of the sets of specified input data for the modular subroutine INITAL (Sects. 6.4, 6.15, and 7.4), the final time T and the final computed values of the principal solution variables in all elements IX = 1, ..., NX and half-elements IMX = 1, ..., 2*NX − 1, and IPX = 1, ..., 2*NX (Sect. 6.15).

```
      WRITE(7,3001)T
3001  FORMAT(4X,E13.6)
```

T = the final time level after NT computational steps, which is equal to the specified actual initial time read by the modular subroutine INITAL (Sects. 6.4 and 7.4) (h).

```
      DO 3010 IX=1,NX
      •
      •
      •
      WRITE(7,3011)IX,HSR(IX),GFX(IMX),GFX(IPX),CRW(IX),CRB(IX)
3011  FORMAT(4X,I3,12X,E11.4,1X,2(1X,E11.4),1X,2(1X,E11.4))
3010  CONTINUE
```

IX = integer designating the element;

HSR(IX) = water surface elevation in the element IX (ft);

GFX(IMX) = channel flow rate in the upstream half-element IMX = 2*NX − 1 (ft^3/h);

GFX(IPX) = channel flow rate in the downstream half-element IPX = 2*NX (ft^3/h);

CRW(IX) = water concentration of the radionuclide in the water layer in the element IX (radiologic unit/ft^3);

CRB(IX) = bottom concentration of the radionuclide in the bottom layer in the element IX (radiologic unit/ft^3).

In applications of the RADONE computer code that require successive short-term simulations, the final output of the modular subroutine OUTPUT, which is written on the output device designated by the logical unit elected by the user, is transferred to the input device designated by the logical unit selected by the user, which is read by the modular subroutine INITAL for restarting the computer simulations (Sects. 6.4 and 7.4).

8.12 DISCUSSIONS OF OUTPUT OF THE AUXILIARY SUBROUTINE STORER

The auxiliary subroutine STORER is called from the modular subroutine OUTPUT at every intermediate time level T, after every NTW time step, and at the final computational time level T, after NT time steps, only for the specified value of the integer control parameter ISTORE = 1, which indicates the user-specified option for storing computed results for the principal flow variables (Sect. 6.15).

STORER writes, on the output device designated by the logical unit selected by the user, according to the exact format of the sets of specified input data for the modular subroutine FLOWER (Sects. 6.17 and 7.5), computed results for the principal solution variables in all the elements IX = 1, ..., NX (Sect. 7.5).

```
      WRITE(6,1001)NDAY
1001  FORMAT(2X,I4)
```

NDAY = day that includes the intermediate output time level T (not the completed day), which corresponds to the specified day of the set of specified input data read by the auxiliary subroutine FLOWER (Sect. 7.5).

STORER writes 25 hourly values of time for each NDAY.

```
1150  WRITE(6,1002)THRDAY,T
1002  FORMAT(2X,F7.2,1X,E13.6)
```

THRDAY = hour of the day during the day NDAY (not the completed day) that corresponds to the intermediate output time level T (h).

T = intermediate output time level at the end of every NTW time step (Sects. 6.15 and 8.11), representing the time since the start of the computer simulations (h).

```
      DO 2010 IX=1,NX
      •
      •
      •
      WRITE(6,2011)IX,HSR(IX),GFSIMX,GFSIPX,CRW(IX),CRB(IX)
2011  FORMAT(1X,I3,E13.6,4(E11.4))
      •
      •
      •
2010  CONTINUE
```

IX = integer designating the element;
HSR(IX) = water surface elevation in the element IX (ft);
GFSIMX = channel flow rate in the upstream half-element IMX = 2*IX − 1 (ft^3);
GFSIPX = channel flow rate in the downstream half-element IPX = 2*IX (ft^3/h);
CRW(IX) = water concentration of the radionuclide in the water layer in the element IX (radiologic unit/ft^3);
CRB(IX) = bottom concentration of the radionuclide in the bottom layer in the element IX (radiologic unit/ft^3).

The output of the auxiliary subroutine STORER automatically provides all necessary sets of specified input data to the auxiliary subroutine FLOWER for hydrodynamic conditions in the main flow channel. Hence, in the applications of the present advanced development program version of the RADONE computer code, the user is not required to prepare any data for the hydrodynamic conditions, provided that the output formats of the auxiliary subroutine STORER and the input formats of the auxiliary subroutine FLOWER are compatible (Sects. 6.16, 6.17, and 7.5).

9. SAMPLE RESULTS OF PRELIMINARY APPLICATIONS OF THE RADONE COMPUTER CODE

The RADONE computer code was applied extensively to the simulation of the flow conditions and radionuclide concentration conditions in the Hudson River estuary during the six-month period of 1 April–30 September in 1973 and 1974. During this six-month period, the flow conditions in the Hudson River were simulated very accurately, within an approximately 2-mile spatial resolution and within a 20-min temporal resolution, in order to include the detailed variations of the periodically reversing tidal flow conditions along the main flow channel of the estuary.

The computer simulation results for the radionuclide concentration conditions along the main flow channel, for the six-month period of 1 April–30 September in 1973, were generated within a spatial accuracy of 2-mile elements and within a temporal accuracy of 20-min. Hence, the results of the computer simulations also generated extremely detailed information about the short-term periodic variations of the radionuclide concentration conditions along the main flow channel which were controlled by the periodically reversing tidal flow conditions in the Hudson River estuary. However, since the available information about the field-measured data of radionuclide concentration conditions in the estuary, during the six-month period of 1 April–30 September in 1973 and 1974 could not indicate short-term variations within the tidal cycles, the computer simulation results of the RADONE computer code were averaged over the 24-h periods to obtain daily-averaged radionuclide concentration conditions in the main flow channel of the estuary.

The preliminary applications of the RADONE computer code considered hypothetical accidental radiological release scenarios for tritium (^{3}H), which required only the consideration of the water concentration of the radionuclide in the water layer, and also strontium (^{90}Sr) and cesium (^{137}Cs), which required considerations of both water concentration of the radionuclide in the water layer and bottom concentration of the radionuclide in the bottom layer along the main flow channel of the Hudson River.

The results of the preliminary applications of the RADONE computer code to the simulation of radionuclide concentration conditions in the Hudson River estuary are presented in various computer graphics output formats in Figs. 9.1–9.13. The sample computer simulation results (Figs. 9.1–9.13) illustrate that the fast-transient (tidal-transient), one-dimensional, two-layer radionuclide transport model and its associated RADONE computer code can be used cost-effectively to generate the detailed and/or averaged information, about the radionuclide concentration conditions in a typical important estuary, after an accidental radiological release, that will be required for radiological dose assessment calculations associated with pathway analyses. The computer simulation results can include

1. Detailed and/or averaged temporal variations of water concentration of the radionuclide in the water layer (a) in the vicinity of the location of the radiological release and (b) at any location upstream or downstream of the location of the radiological release along the estuary (Figs. 9.1–9.3, 9.12, and 9.13). This information can be used directly in first-order, direct-pathway analyses concerned with short-term health safety problems associated with contaminated water conditions in the vicinities of the intakes of water supply systems along the estuary.
2. Detailed and/or averaged spatial distributions of water concentration of the radionuclide in the water layer along the complete length of the main flow channel at any time during and after an accidental radiological release into the estuary (Figs. 9.4–9.8). This information is required to understand the cumulative effect of the flow phenomenon that transports the radionuclide along the main flow channel and, particularly, the critically important flushing effect, associated with periodically reversing tidal flow conditions, which contributes significantly to the natural transportive decontamination process that continuously occurs in a tidal estuary.

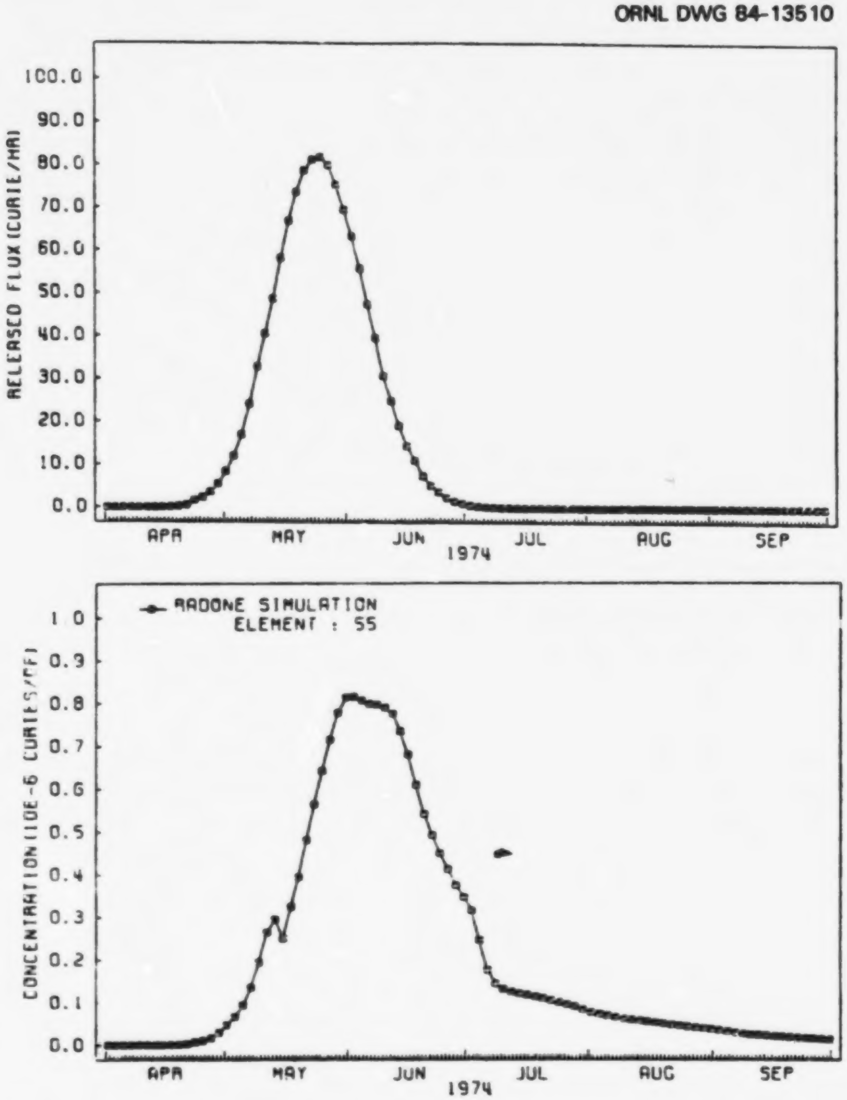

Fig. 9.1. Release conditions of tritium (^3H) in the Hudson River, 1 April–30 September 1974: (*a*) specified hypothetical prompt release conditions at location 42 miles upstream of ocean end and (*b*) computer simulation results of daily-averaged ^3H concentration at release location.

3. Detailed and/or averaged spatial distributions of bottom concentration of the radionuclide in the bottom layer along the complete length of the main flow channel at any time during and after an accidental radiological release into the estuary (Figs. 9.9 and 9.11). This information is required to estimate the local rates of accumulation and local residence times of the radionuclide in the bottom matter of the bed in different subregions of the main flow channel, in order to initiate the radiological dose assessment calculations, associated with complex food-chain pathway analyses concerned with long-term health safety problems.

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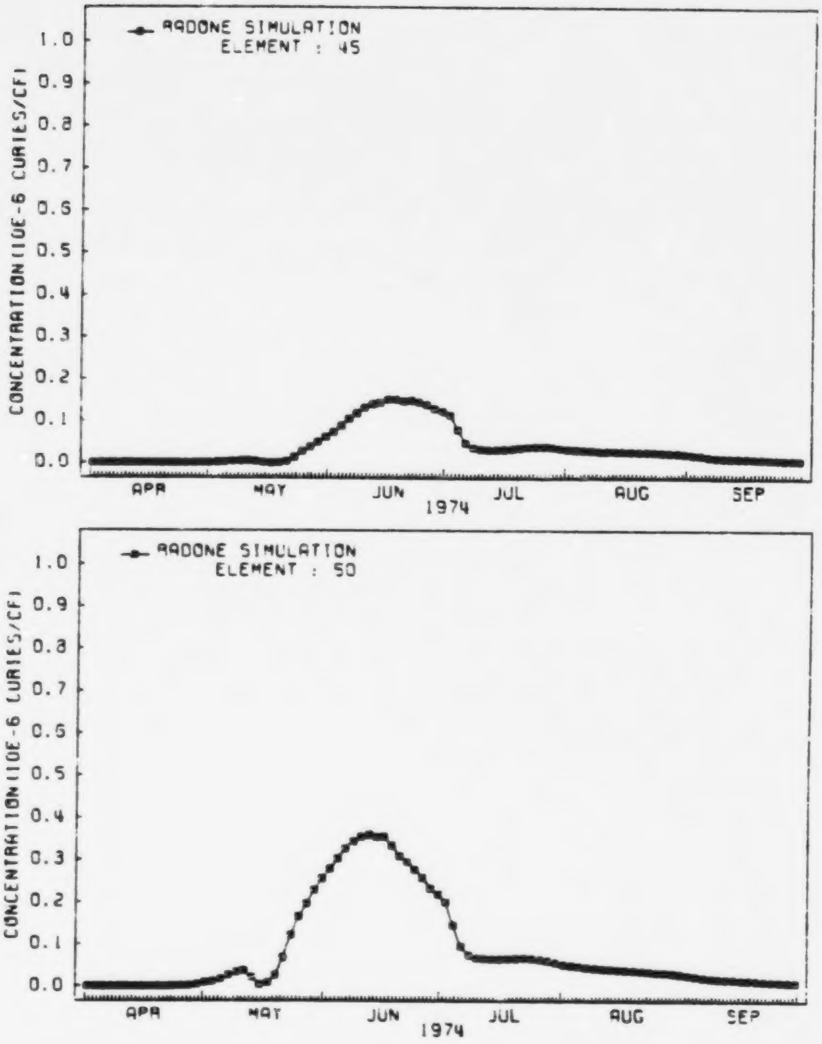

Fig. 9.2. Computer simulation results of daily-averaged tritium (^3H) concentration in the Hudson River, 1 April–30 September 1974: (*a*) 20 miles upstream of release location and (*b*) 10 miles upstream of release location.

The preliminary applications of the RADONE computer code to the simulation of the radionuclide concentration conditions in the Hudson River estuary, with actual radiological release conditions at Indian Point, during the six-month period 1 April–30 September 1973 (Figs. 9.12 and 9.13), also indicates that the fast-transient (tidal-transient), one-dimensional, two-layer radionuclide transport model can be used as a predictive tool for the assessment of radiological impact.

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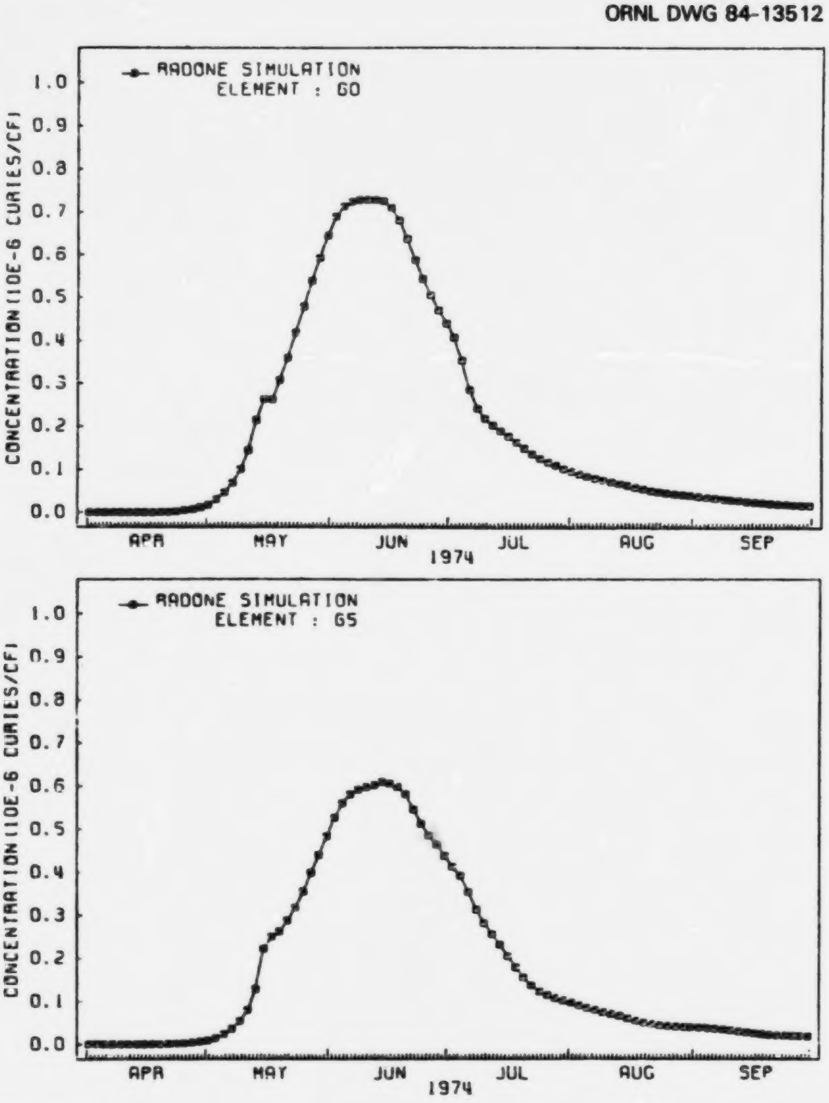

Fig. 9.3. Computer simulation results of daily-averaged tritium (^{3}H) concentration in the Hudson River, 1 April–30 September 1974: (*a*) 10 miles downstream of release location and (*b*) 20 miles downstream of release location.

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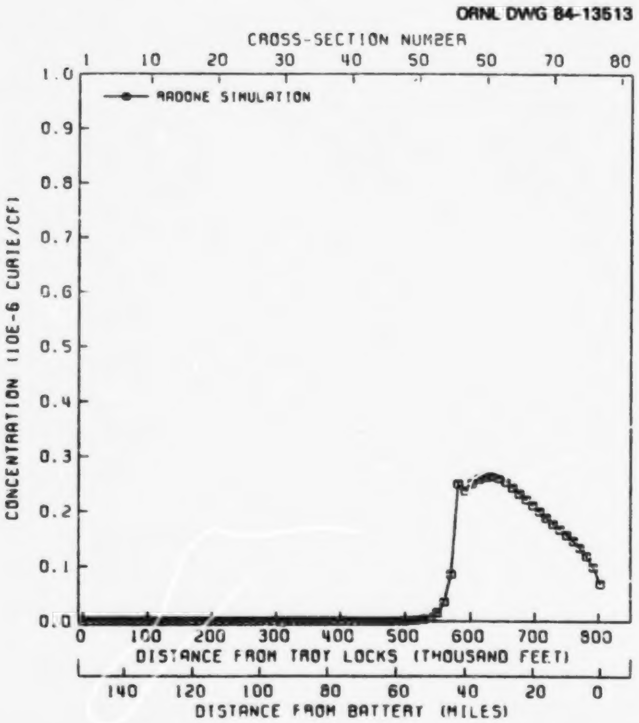

Fig. 9.4. Computer simulation results for longitudinal distribution of daily-averaged tritium (^{3}H) concentration on 15 May 1974 (9 d before occurrence of maximum release conditions) along the Hudson River.

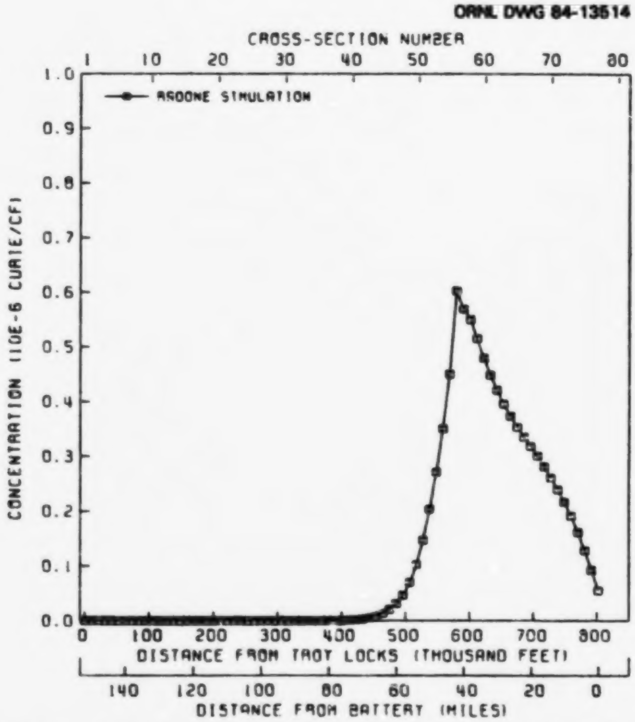

Fig. 9.5. Computer simulation results for longitudinal distribution of daily-averaged tritium (^{3}H) concentration on 24 May 1974 (on the day of occurrence of maximum release conditions) along the Hudson River.

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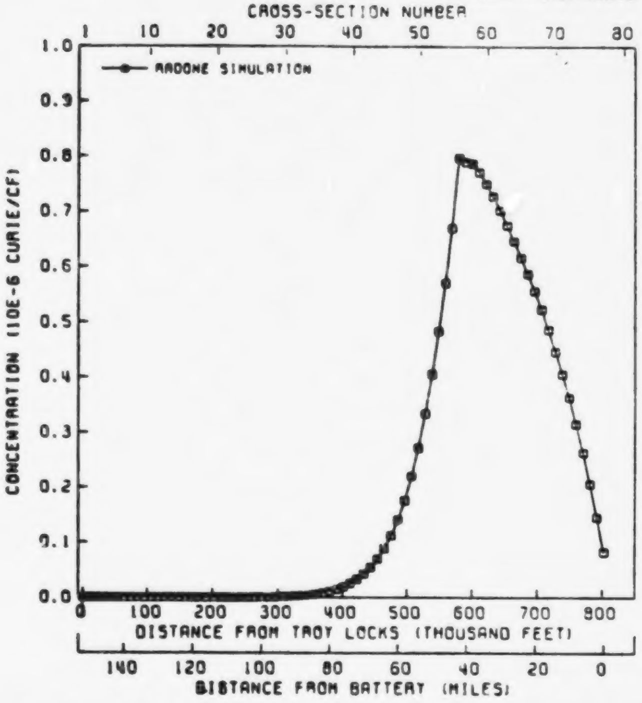

Fig. 9.6. Computer simulation results for longitudinal distribution of daily-averaged tritium (^{3}H) concentration on 8 June 1974 (15 d after occurrence of maximum release conditions) along the Hudson River.

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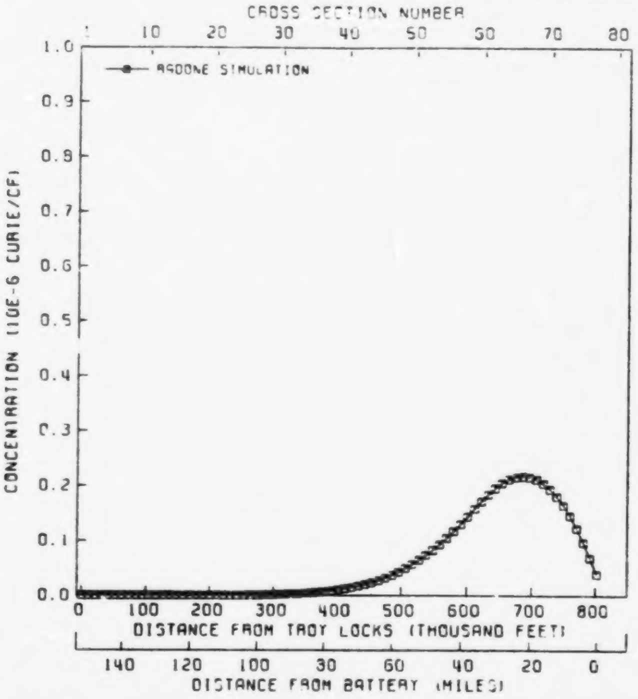

Fig. 9.7. Computer simulation results for longitudinal distribution of daily-averaged tritium (^{3}H) concentration on 15 August 1974 (83 d after occurrence of maximum release conditions) along the Hudson River.

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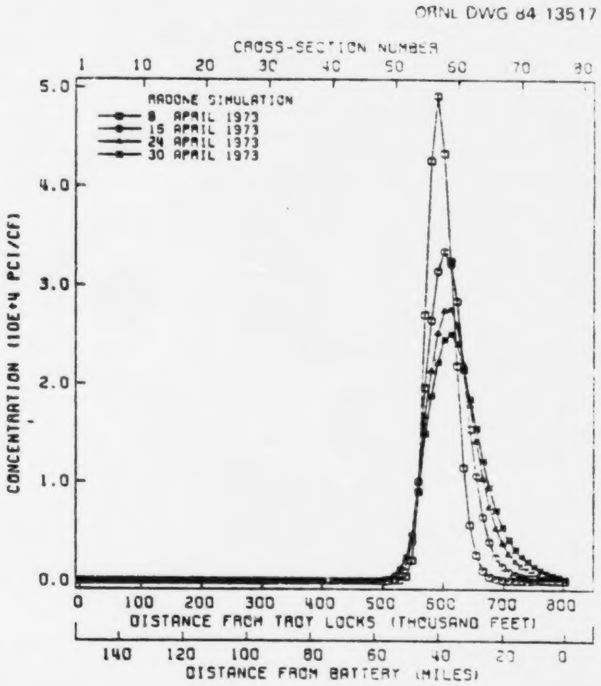

Fig. 9.8. Computer simulation results for longitudinal distribution of daily-averaged water concentration of cesium (^{137}Cs) in the water layer, during April 1973, along the Hudson River (simulation of actual radionuclide release scenario).

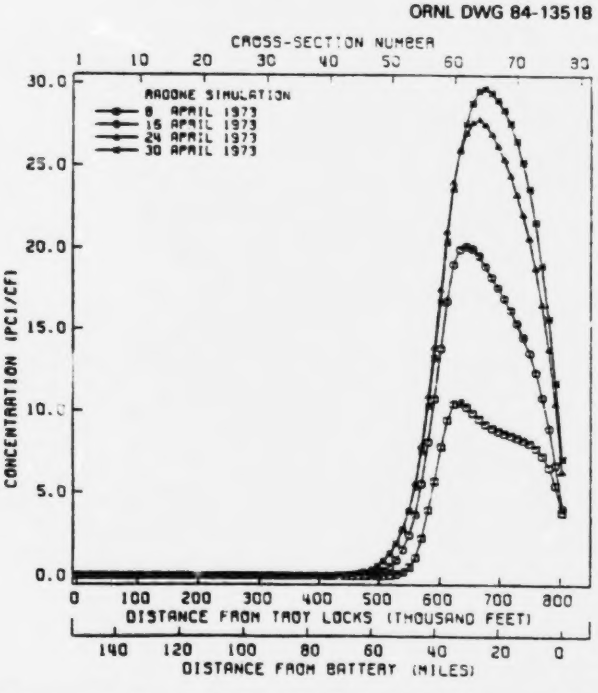

Fig. 9.9. Computer simulation results for longitudinal distribution of daily-averaged bottom concentration of cesium (^{137}Cs) in the bottom layer, during April 1973, along the Hudson River (simulation of actual radionuclide release scenario).

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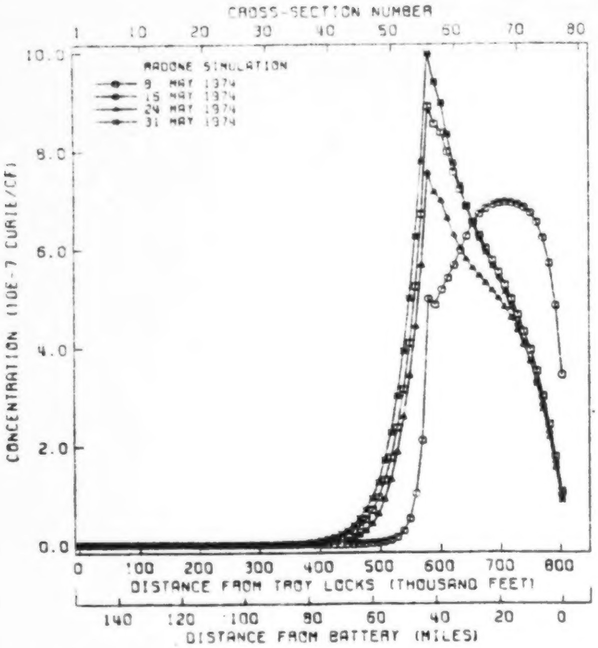

Fig. 9.10. Computer simulation results for longitudinal distribution of daily-averaged water concentration of strontium (^{90}Sr) in the water layer, during May 1974, along the Hudson River (simulation of hypothetical radionuclide release scenario).

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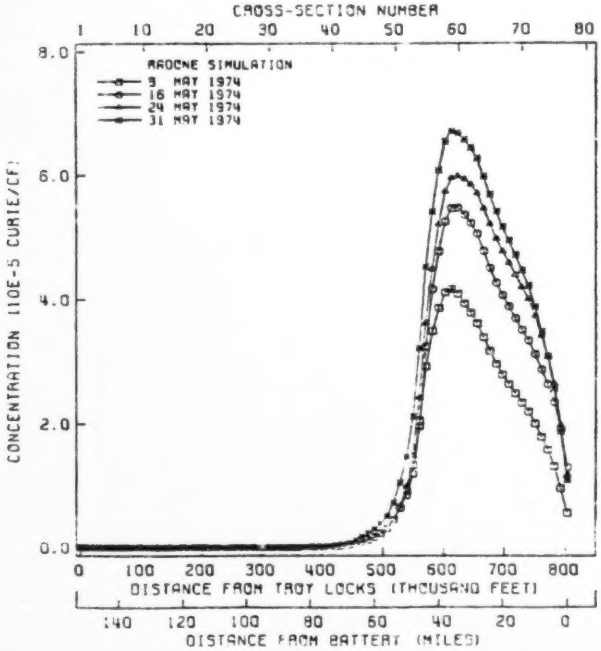

Fig. 9.11. Computer simulation results for longitudinal distribution of daily-averaged bottom concentration of strontium (^{90}Sr) in the bottom layer, during May 1974, along the Hudson River (simulation of hypothetical radionuclide release scenario).

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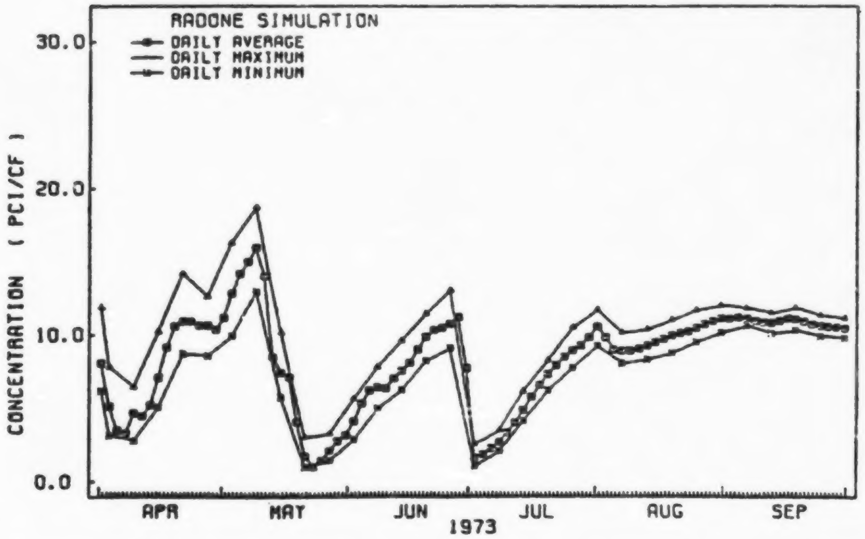

Fig. 9.12. Computer simulation results for variation of water concentration of cesium (^{137}Cs) in the water layer, during April–September 1973, in the vicinity of Indian Point in the Hudson River (simulation of actual radionuclide release scenario).

ORNL DWG 84-13522

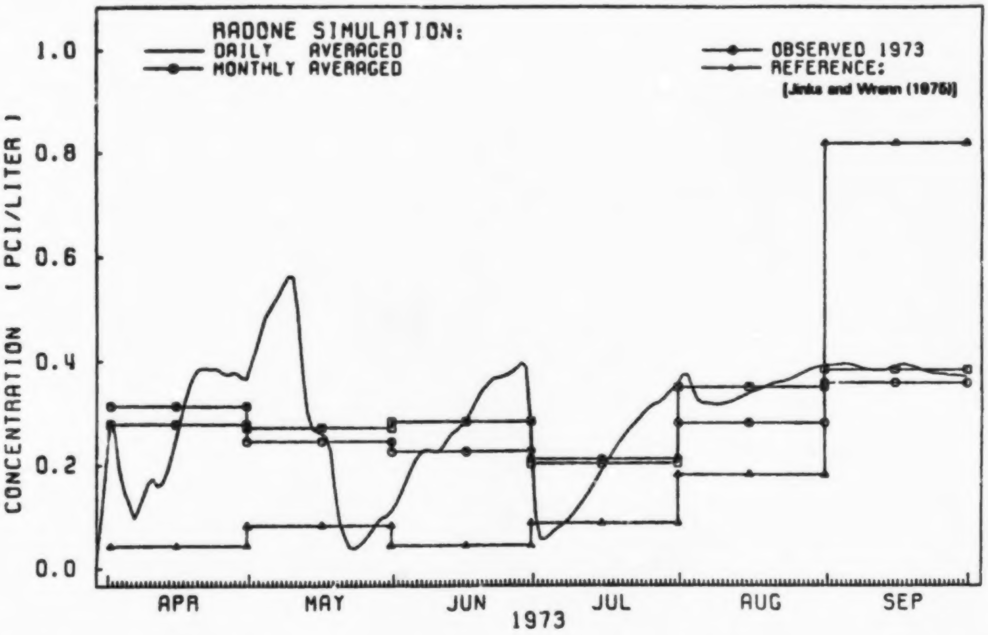

Fig. 9.13. Comparison of computer simulation results and field-measured data (modified and combined) for variation of water concentration of cesium (^{137}Cs) in the water layer, during April–September 1973, in the vicinity of Indian Point in the Hudson River (simulation of actual radionuclide release scenario). *Source:* S. M. Jinks and M. E. Wrenn, "Radiocesium Transport in the Hudson River Estuary," Chap. 11 in *Environmental Toxicity of Aquatic Radionuclides: Models and Mechanisms,* ed. M. W. Miller and J. N. Stannard, Ann Arbor Science Publishers, Ann Arbor, Mich., 1973.

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10. CONCLUSIONS AND RECOMMENDATIONS

The computational algorithm of the RADONE computer code represents a fast-transient (tidal-transient), one-dimensional, two-layer radionuclide transport model for simulating detailed hydrodynamic conditions and radionuclide concentration conditions in the main flow channel of a controlled-river or a tidal estuary.

The first important mathematical feature of the fast-transient, one-dimensional, two-layer radionuclide transport model is that the formulation of its spatially discretized, governing system of equations is based on the one-dimensional form of the discrete-element method (DEM), which guarantees the satisfaction of the essential criteria of local conservation of water mass, momentum, and radionuclide mass (including the effect of radiological decay) for every computational element. Hence, the discrete-element formulation of the fast-transient, one-dimensional, two-layer radionuclide transport model is significantly superior to the radionuclide transport models based on the finite-element method (DEM), which can only satisfy the conservation criteria in the average sense, over the entire computational region, but not necessarily for each computational element. Provided that the specified flow conditions, associated with the streams (or tributaries) and the intakes and discharges of plants, into or out of the water layer and the bottom layer, are appropriately specified to guarantee the satisfaction of the local conservation criterion for the water mass in each element, the discrete-element formulation of the fast-transient, one-dimensional radionuclide transport model automatically satisfies all criteria for local conservation of water mass, momentum, and radionuclide mass (including the effect of radiological decay) in every computational element and for all time during the numerical integration of the governing computational system of discrete-element equations. Therefore, the fast-transient, one-dimensional, two-layer radionuclide transport model of the RADONE computer code completely eliminates the possibility of encountering computationally generated, artificial, local "leaking" problems, associated with water mass, and local "generation" or "destruction" problems, associated with the radionuclide mass, during the simulations of flow conditions and radionuclide concentration conditions in the main flow channel of a river or an estuary.

The second important mathematical feature of the fast-transient, one-dimensional, two-layer radionuclide transport model is that its formulation incorporates, approximately but realistically, the important effect of bottom radionuclide uptake and release conditions, by considering a physically plausible submodel for the bottom radionuclide transport effects, consisting of (1) the bottom radionuclide transport effect, (2) the bottom-settling (deposition) radionuclide transport effect, and (3) the bottom-resuspension (scouring) radionuclide transport effect, between two layers defined as (a) the water layer and (b) the bottom layer in every element of the main flow channel. The mathematical formulation explicitly considers the temporal variations of two radionuclide concentrations as (1) the water concentration of the radionuclide in the water layer and (2) the bottom concentration of the radionuclide in the bottom layer, in each element, based on rigorous formulations of two separate conservation principles for the radionuclide mass (including the effect of radiological decay) in each layer. Furthermore, the mathematical formulation utilizes the physically plausible submodel for the bottom radionuclide transport effects for representing the net rate of exchange of radionuclide mass, between the water layer and the bottom layer, by considering (a) eddy-turbulent (or laminar) mixing conditions at the bottom, (b) effective full velocity conditions, and (c) effective resuspension velocity conditions, associated with the lumped sediment-organic-matter class, which can contain the radionuclide in sorbed (adsorbed and/or absorbed) states in the two layers of the main flow channel. Therefore, since the mathematical formulation explicitly considers two distinct conservation principles for the radionuclide mass, in two distinctly defined layers, in each element, the fast-

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transient, one-dimensional, two-layer radionuclide transport model completely eliminates the possibility of encountering errors that may be introduced into the single-layer models, which incorporate physically unrealistic bottom radionuclide uptake and release effects, without explicitly accounting for the radionuclide mass taken out of, or introduced into, the single-layer, one-dimensional flow region of the main flow channel.

In preliminary applications of the RADONE computer code, all specified values for the coefficients and parameters used in the formulation of the bottom radionuclide transport submodel were selected based on realistic estimates, since actual site-specific information about the detailed sediment conditions and/or organic-matter conditions were not readily available for rivers and estuaries considered in the studies. Therefore, it is recommended that studies of modest scope and cost be undertaken to survey all available field-measured data about the detailed sediment concentration and transport conditions and if appropriate about the organic-matter concentration and transport conditions in a selected number of controlled-flow rivers and tidal estuaries that serve as the receiving water bodies for the condenser cooling water systems of important nuclear power plants in the United States. The results of these studies, combined with more extensive studies that would use the results of computer simulations of flow conditions and radionuclide concentration conditions by the application of the RADONE computer code, will allow for the establishment of accurate and reliable values for the coefficients and parameters used in the formulation of the bottom radionuclide transport submodel, for different important radionuclides that may be introduced into these receiving water bodies as consequences of actual accidental or controlled radionuclide release scenarios.

The third important mathematical feature of the fast-transient, one-dimensional, two-layer radionuclide transport model is that its formulation, based on DEM, can develop explicit forms for (1) convection-defect radionuclide transport rate and (2) eddy-turbulent radionuclide transport rate, as two distinctly separated radionuclide transport rates, across the cross-sectional area of each enclosure surface of each element of the main flow channel of a river or an estuary. The formulation rigorously considers the vertical and lateral variations of the channel flow velocity and water concentration of the radionuclide in the water layer based on approximate but physically plausible, locally self-similar distributional forms, associated with turbulent flow conditions, and in terms of the local concentration difference, between the water concentration of the radionuclide in the water layer and the bottom concentration of the radionuclide in the bottom layer, over the cross-sectional area of each enclosure surface of each element. Hence, the formulation approximately but realistically incorporates the vertical and lateral variations of the channel flow velocity and water concentration of the radionuclide in the water layer in the development of the two separate parts of the overall nonconvective radionuclide transport rate as (1) convection-defect radionuclide transport rate and (2) eddy-turbulent radionuclide transport rate without resorting to any ad hoc assumption about the overall dispersion phenomenon that can control the transport of the radionuclide along a river or an estuary. The important consequence of this formulation is that it completely eliminates the need for arbitrarily estimating questionable values for inherently site-specific dispersion coefficients that may vary differently along the main flow channels, depending on different variations, of depth and detailed geometrical characteristics of different cross sections of different rivers and estuaries. In general, it is established that the concept of dispersion coefficient can only be marginally acceptable under very restrictive flow conditions (and distributional conditions over the cross sections) and only for passive contaminants that can exist only in the dissolved state in the main flow channel of a river or an estuary. Therefore, the simplistic formulations of the longitudinal dispersion radionuclide transport rates, used in most conventional one-dimensional radionuclide transport models, in terms of estimated constant dispersion coefficients, according to ad hoc assumptions, must be concluded as extremely questionable, based on considerations of the radionuclide transport conditions, which may be controlled by the bottom radionuclide uptake and release conditions of the sorbed (adsorbed and/or absorbed) states of the radionuclide in the main flow channel of an actual river or estuary. The fast-transient, one-dimensional, two-layer radionuclide transport model of the RADONE computer code completely discards the use of questionable dispersion coefficients, which can introduce appreciable error in the computational results, by incorporating explicitly formulated (1) convection-defect radionuclide transport rates and (2) eddy-turbulent radionuclide transport rates in the formulation of the nonconvective radionuclide transport rates along the main flow channel; therefore, it is superior to all conventional one-dimensional radionuclide transport models in simulating the flow conditions and radionuclide concentration conditions in actual rivers and estuaries.

The present version of the RADONE computer code must be classified as a "development program" version of the computational algorithm of the fast-transient, one-dimensional, two-layer radionuclide transport model for controlled-flow rivers and tidal estuaries. Therefore, the structure and the computational procedure of the RADONE computer code cannot be considered as optimized from FORTRAN programming considerations. The present development program version is extensively compartmentalized in the forms of modular subroutines, and it also includes certain computational features that are essential to guarantee the reliability of the computational algorithm in duplicating the mathematical formulation of the radionuclide transport model. Hence, the development program version of the RADONE computer code requires certain excess amounts of central processing unit (CPU) time and storage which can be readily eliminated by optimizing the structure and procedure of the computational solution algorithm based on established efficient FORTRAN programming considerations. A completely optimized "production program" version can be developed cost-effectively based on the presently available development program version of the RADONE computer code. The production program version of the RADONE computer code can significantly reduce the cost of applications of the fast-transient, one-dimensional, two-layer radionuclide transport model to the assessment of the radiological impact on the receiving water body that would result from accidental or controlled radiological releases into a river or an estuary.

The computational solution algorithm of the development program version of the RADONE computer code uses the fourth-order Runge-Kutta-Gill numerical integration technique, which represents an explicit, four-step, three-time-level method for advancing the time level of the numerical solutions. This particular numerical integration method was selected for the development program version of the RADONE computer code to guarantee accurate numerical solutions for relatively fast decay rate conditions of certain important radionuclides. However, since the fourth-order Runge-Kutta-Gill numerical integration method does not necessarily improve the stability characteristics of the numerical solutions of the governing system of discrete-element equations and, furthermore, since the term representing the first-order radiological decay rate can be eliminated by considering a relatively simple transformation of the definition of the radionuclide concentrations, it would be computationally cost-effective to replace the Runge-Kutta-Gill method by a more advanced but not necessarily more complex numerical solution algorithm. The computationally efficient, explicit, two-step, three-time-level, composite-time-splitting numerical integration method, with extremely reliable stability characteristics, which was developed for more advanced, multidimensional transport models of the Unified Transport Approach (UTA) project can be readily incorporated in the production program version of the RADONE computer code.

The present formulation of the fast-transient, one-dimensional, two-layer radionuclide transport model uses the conventional second-upwind differencing interpolation technique in the computation of the convective radionuclide transport rates on the enclosure surfaces of the elements. This well-established interpolation technique can introduce numerical dispersion effects into the computational solutions of the water concentration of the radionuclide in the water layer in certain elements where the existing low flow conditions can reduce the local value of the effective Courant number substantially below the expected value of unity for the user-specified constant value of the time step of numerical integration. The second-order, transportive-upwind-differencing interpolation technique, which was developed for more advanced, multidimensional transport models of the UTA project, can be readily incorporated in the production program version of the RADONE computer code, in order to completely eliminate the numerical dispersion effect in the simulations of the radionuclide concentration conditions in a river or an estuary.

The RADONE computer code was specifically structured to enable the user to implement the model in computer simulations of flow conditions and radionuclide concentration conditions in actual rivers and estuaries. Hence, the input data formats of the RADONE computer code have all the necessary capabilities to incorporate wide ranges of information about the physical and climatological conditions and the radiological conditions in the geographic region of the main flow channel that could control the flow conditions and radionuclide concentrations in a river or an estuary. The user can readily implement the RADONE computer code with extensive sets of specified input data for end conditions, climatological conditions, stream and tributary flow conditions, groundwater seepage flow conditions, and plant operational conditions for extremely accurate computer simulations of the flow conditions and radionuclide concentrations in an actual river or an estuary for any selected time period during and after any actual or hypothetical, accidental or controlled radiological release scenario. However, the user can also readily implement the RADONE computer code with very simple and limited sets of specified input data in applications that require only approximate but realistic computer simulations of flow conditions and radionuclide concentration conditions in an open channel or in a river or estuary with a geometrically simple main flow channel. Indeed, the RADONE computer code can use directly the simple and limited sets of specified data required for the applications of most presently available, relatively simple, conventional one-dimensional radionuclide transport models. Hence, although the RADONE computer code has all the necessary capabilities to incorporate detailed and accurate sets of specified input data, it is definitely not limited in its application with simplified sets of specified input data for the simulation of flow conditions and radionuclide concentration conditions in controlled-flow rivers and tidal estuaries. It is recommended that studies of modest scope and cost be undertaken to apply the RADONE computer code and a selected set of presently available, conventional one-dimensional radionuclide transport models to the simulation of radionuclide concentration conditions in a selected set of controlled-flow rivers and estuaries for which reliable field-measured data for radiological release conditions and temporal and spatial variations of radionuclide concentration conditions are available. The results of these studies will establish the capabilities and limitations of the presently available one-dimensional radionuclide transport models. Furthermore, the results of these studies will indicate the geometrical conditions of the flow channel and the flow conditions in a controlled-flow river or an estuary that will require the application of multidimensional radionuclide transport models and, hence, the limiting conditions for the application of one-dimensional radionuclide transport models. A preliminary study for the validation of the RADONE computer code based on comparison of the computer simulations with the available field-measured data for radionuclide concentration conditions in the Hudson River estuary has been initiated. The computer simulation results of the preliminary applications clearly illustrated the capabilities of the RADONE computer code in predicting radionuclide concentration conditions in an estuary where the flow conditions exhibit relatively complex, periodically reversing tidal conditions. It is recommended that this study be completed to establish a working radionuclide transport model for the Hudson River estuary, which serves as the receiving water body for the Indian Point Nuclear Station.

In summary, the RADONE computer code can be considered as an advanced fast-transient, one-dimensional, two-layer radionuclide transport model for simulating accurately the flow conditions and radionuclide concentration conditions in controlled-flow rivers and tidal estuaries. The radionuclide transport model can be used as a reliable predictive tool for the assessment of radiological impact on the receiving water body that would result from accidental or controlled radiological releases into any river or an estuary. The RADONE computer code can be readily implemented in studies concerned with the radiological impact of accidental releases from most major nuclear power plants operating on controlled-flow rivers and estuaries, including *Three-Mile Island Nuclear Station on the Susquehanna River, Peach Bottom Nuclear Power Station on the Susquehanna River, Indian Point Nuclear Station on the Hudson River, Browns Ferry Nuclear Station on the Tennessee River,* and other nuclear power plants selected by the U.S. Nuclear Regulatory Commission.

REFERENCES

Barnthouse, L. W., et al. July 1977. *A Selective Analysis of Power Plant Operation on the Hudson River with Emphasis on the Bowline Point Generating Station* (2 vols.), ORNL/TM-5877, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Bellman, R. 1956. "Equilibrium Analysis: The Stability Theory of Poincaré and Liapunov," pp. 30–35 in *Modern Mathematics for the Engineer,* ed. E. F. Beckenbach, McGraw, New York.

Bolg, R. E., and G. L. Tuve, eds. 1970. *Handbook of Tables for Applied Engineering Science,* The Chemical Rubber Co., Cleveland, Ohio, p. 584.

Boyd, M. B., et al. 1973. *Enlargement of the Chesapeake and Delaware Canal,* Technical Report H-73-16, U.S. Army Engineer Waterways Experiment Station, Hydraulics Laboratory.

Churchill, J. H. December 1976. "Measurements and Computer Modeling of the Distribution of Nuclear Reactor Discharged Radionuclides in the Estuarine Sediment Near the Maine Yankee Atomic Power Plant in Wiscasset, Maine," MS thesis, Physics Department, University of Maine-Orono.

Churchill, R. V. 1941. *Fourier Series and Boundary Value Problems,* McGraw, New York.

Conte, S. D., and C. deBoor. 1972. *Elementary Numerical Analysis: An Algorithmic Approach,* 2d ed., McGraw, New York.

Courant, R., K. O. Friedrichs, and H. Lewy. 1928. "Über die Partiellen Differenzengleichungen der Mathematischen Physik," *Mathematischen Annalen* **100**: 32–74.

Courant, R., K. O. Friedrichs, and H. Lewy. March 1967. "On the Partial Difference Equations of Mathematical Physics," *IBM J.,* 215–34.

Dailey, J. E., and D. R. F. Harleman. 1972. *Numerical Model for the Prediction of Transient Water Quality in Estuary Networks,* R. M. Parsons Laboratory for Water Resources and Hydrodynamics, Department of Civil Engineering, Massachusetts Institute of Technology Report No. 158, Cambridge.

Daily, J. W., and D. R. F. Harleman. 1966. *Fluid Dynamics,* Addison-Wesley, Reading, Mass.

Daniels, D. B., J. C. Sonnichsen, and R. T. Jaske. 1970. *The Estuarine Version of the COLHEAT Digital Simulation Model,* Atomic Energy Commission Research and Development Report BNWL-1342, Battelle Pacific Northwest Laboratories, Richland, Wash.

Dronkers, J. J. 1964. *Tidal Computations in Rivers and Coastal Waters,* North-Holland, Amsterdam.

Edinger, J. E., and J. C. Geyer. 1965. *Heat Exchange in the Environment,* Research Project RP-49, Department of Sanitary Engineering and Water Resources, Johns Hopkins University, Baltimore.

Edinger, J. E. 1971. "Estuarine Temperature Distribution," Chap. IV in *Estuarine Modeling: An Assessment,* ed. G. H. Ward, Jr., and W. H. Espey, Jr., Water Control Research Series 16070DZV, Tracor, Inc., Austin, Tex.

"Effect of Three Unit Operation at Indian Point on Hudson River Temperature Distribution," 1972. Appendix DD in *Indian Point Unit No. 3, Environmental Report,* prepared by Lawler, Matusky, and Skelly Engineers, New York, 1972.

Eraslan, A. H. 1974. *Transient, Two-Dimensional Discrete-Element, Far-Field Model for Thermal Impact Analysis of Power Plant Discharges in Coastal and Offshore Regions. Part I: General Description of the Mathematical Model and the Results of an Application*, ORNL-4940, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Eraslan, A. H. 1975. "A Transient, Two-Dimensional Discrete-Element Model for Far-Field Analysis of Thermal Discharges in Coastal Regions," pp. 165–201 in *Progress in Astronautics and Aeronautics*, vol. 36, ed. J. A. Schetz, AIAA, New York.

Eraslan, A. H. June 6–8, 1976. "Discrete-Element Models for Thermal Impact Assessment of Large Power Plants in Estuaries and Coastal Regions," in *Proceedings of the 12th Southeastern Seminar on Thermal Sciences, Charlottesville, Va.*

Eraslan, A. H., and H. Diament. July 1984 (DRAFT). *RADTWO: A Computer Code for Simulating Fast-Transient, Two-Dimensional, Two-Layer Radionuclide Concentration Conditions in Lakes, Reservoirs, Rivers, Estuaries, and Coastal Regions*, ORNL/TM-8869, NUREG/CR-3442, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Eraslan, A. H., et al. 1976. *A Computer Simulation Model for the Striped Bass Young-of-the-Year Population in the Hudson River*, ORNL/NUREG-8, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Eraslan, A. H., et al. 1977. *Development of a Unified Transport Approach for the Assessment of Power-Plant Impact*, ORNL/NUREG/TM-89, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Eraslan, A. H., and K. H. Kim. December 4–6, 1978. "Cost-Effective Mathematical Modeling for Assessment of Hydrodynamic and Thermal Impact of Power Plant Operations on Controlled Flow Reservoirs," *Proceedings of the Second Conference on Waste Heat Management and Utilization, Miami, Florida*, p. IV-A-3.

Eraslan, A. H., I. H. Erhan, and W-L. Lin. January 1981. "A Supplementary Study of the Impact of Power-Plant Operation on the Hudson River with Emphasis on Bowline Point Generating Station," Appendix E in *Final Environmental Impact Statement, Bowline Point Generating Station, Haverstraw, New York*, Department of the Army, New York District Corps of Engineers, New York.

Eraslan, A. H., and R. D. Sharp. 1982. *STRIPE: A Computer Code for Simulating Tidal-Averaged, One-Dimensional Concentrations of Striped Bass Young-of-the-Year Life-Stage Populations in the Hudson River*, ORNL/NUREG/TM-423 (NUREG/CR-1830), Oak Ridge National Laboratory, Oak Ridge, Tenn.

Eraslan, A. H. November 1983. *ESTONE: A Computer Code for Simulating Fast-Transient, One-Dimensional Hydrodynamic, Thermal and Salinity Conditions in Controlled Rivers and Tidal Estuaries for the Assessment of the Aggregated Impact of Multiple Power Plant Operation*, ORNL-5691 (NUREG/CR-2621), Oak Ridge National Laboratory, Oak Ridge, Tenn.

Eraslan, A. H., W-L. Lin, and R. D. Sharp. December 1983. *FLOWER: A Computer Code for Simulating Three-Dimensional Flow, Temperature, and Salinity Conditions in Rivers, Estuaries, and Coastal Regions*, NUREG/CR-3172.

Eraslan, A. H., and A. J. Witten. June 1984 (DRAFT). *An Overview of the Unified Transport Approach*, ORNL/TM-9249 (NUREG/CR-3871), Oak Ridge National Laboratory, Oak Ridge, Tenn.

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Fields, D. E., and C. M. Hetrick. 1977. *HOSTED—A One-Dimensional Tidal-Transient Discrete Element Model for Simulating Hydrodynamic Conditions and Adsorbed and Dissolved Radioisotope Concentration in Controlled Rivers and Estuaries,* ORNL/CSD-16, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Fisher, S. K., et al. April 1984. *CHMONE: A One-Dimensional Computer Code for Simulating Temperature, Flow, and Chemical Concentrations in Water Bodies,* NUREG/CR-3410.

Goldstein, S. 1938. *Modern Developments in Fluids Dynamics,* Clarendon Press, Oxford.

Grove, D., et al. December 1970. *A Method to Describe the Flow of Radioactive Ions in Groundwater,* SC-CR-70-6139, U.S. Geological Survey in collaboration with Sandia Corporation.

Haag, F. G., and K. W. Bedford. 1971. "Transport Equation Stability and Estuary Modeling," *J. Hydraulics Division, ASCE* 97(12): 2051–65.

Harleman, D. R. F. 1966. "Tidal Dynamics in Estuaries, Part II: Real Estuaries," Chap. X in *Estuary and Coastline Hydrodynamics,* ed. A. T. Ippen, McGraw, New York.

Harleman, D. R. F., and A. T. Ippen. 1967. *Two-Dimensional Aspects of Salinity Intrusion in Estuaries: Analysis of Salinity and Velocity Distributions,* Technical Bulletin No. 13, Committee on Tidal Hydraulics, U.S. Army Corps of Engineers.

Harleman, D. R. F., C. H. Lee, and L. C. Hall. 1968. "Numerical Studies of Unsteady Dispersion in Estuaries," *J. Sanit. Eng. Div., Am. Soc. Civ. Eng.* 94(SA5): 897–911.

Harleman, D. R. F., and C. H. Lee. 1969. *The Computation of Tides and Currents in Estuaries and Canals,* Technical Bulletin No. 16, Committee on Tidal Hydraulics, U.S. Army Corps of Engineers.

Harleman, D. R. F. 1971. "One-Dimensional Models," pp. 34–89 in *Estuarine Modeling: An Assessment,* ed. G. H. Ward, Jr., and W. H. Espey, Jr., Water Control Research Series 16070DZV, Tracor, Austin, Tex.

Harleman, D. R. F., et al. 1972. *Application of the M.I.T. Transient Salinity Intrusion Model to the Hudson River Estuary,* R. M. Parsons Laboratory for Water Resources and Hydrodynamics, Department of Civil Engineering, Massachusetts Institute of Technology Report No. 153, Cambridge.

Harleman, D. R. F., D. N. Brocard, and T. O. Najarian. 1973. *A Predictive Model for Transient Temperature Distributions in Unsteady Flows,* R. M. Parsons Laboratory for Water Resources and Hydrodynamics, Department of Civil Engineering, Massachusetts Institute of Technology, Technical Report No. 175, Cambridge.

Harlow, F. H., and J. E. Welch, 1965. "Numerical Calculation of Time-Dependent Viscous Incompressible Flow of Fluid with Free Surface," *Phys. Fluids* 8(12): 2182–89.

Harlow, F. H., and A. A. Amsden. 1970. *Fluid Dynamics: An Introductory Text,* Los Alamos Scientific Laboratory, LA-4100, Los Alamos, N. Mex.

Hendershott, M., and W. Munk. 1970. "Tides," pp. 205–224 in *Annual Review of Fluid Mechanics, Vol. 2,* ed. M. Van-Dyke, W. G. Vincenti, and J. V. Wehausen, Annual Reviews, Palo Alto, Calif.

Hetrick, D. M., A. H. Eraslan, and M. R. Patterson. 1979. *SEDONE: A Computer Code for Simulating Tidal-Transient, One-Dimensional Hydrodynamic Conditions and Three-Layer, Variable-Size Sediment Concentrations in Controlled Rivers and Tidal Estuaries,* NUREG/CR-0430, ORNL/NUREG/TM-256, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Hirt, C. W. 1968. "Heuristic Stability Theory for Finite-Difference Equations," *J. Comp. Phys.* **2**: 339–55.

Holderman, J. T., Jr. 1977. *PREPR2: A Program to Aid in the Preparation of Input Data for the Farout Hydraulic Transport Code,* ORNL/CSD/TM-19, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Hunter, J. R. 1975. *A One-Dimensional Dynamic and Kinematic Numerical Model Suitable for Canals and Estuaries,* Ref. 75-10, Special Report 47, Chesapeake Bay Institute, Johns Hopkins University, Baltimore.

Indian Point Nuclear Generating Station Report on the Evaluation of Hydrothermal Studies. 1976. Prepared by Consolidated Edison Company of New York, New York.

Jinks, S. M., and M. E. Wrenn. 1973. "Radiocesium Transport in the Hudson River Estuary," Chap. 11, *Environmental Toxicity of Aquatic Radionuclides: Models and Mechanisms,* ed. M. W. Miller and J. N. Stannard, Ann Arbor Science Publishers, Ann Arbor, Mich.

Lai, C. 1967. "Computation of Transient Flows in Rivers and Estuaries by the Multiple-Reach Method of Characteristics," in *Geological Survey Research 1967,* U.S. Geol. Surv. Prof. Paper 575-D, D273–D280.

Leendertse, J. J. 1967. *Aspects of a Computational Model for Long Period Water Wave Propagation,* The Rand Corporation, RM-5294-PR, New York.

Leendertse, J. J. 1970. *A Water-Quality Simulation Model for Well-Mixed Estuaries and Coastal Seas: Vol. I. Principles of Computation,* The Rand Corporation, RM-6230-RC, New York.

Leendertse, J. J. 1971. "Digital Techniques: Finite Differences," in *Estuarine Modeling: An Assessment,* ed. G. H. Ward, Jr., and W. H. Espey, Jr., Water Control Research Series 16070DZV, U.S. Environmental Protection Agency, Tracor, Austin, Tex.

Leendertse, J. J., and S. K. Liu. Sept. 3–5, 1975. "Modeling of Three-Dimensional Flows in Estuaries," presented at the Symposium on Modeling Techniques for Waterways, Harbors, and Coastal Engineering, San Francisco.

Lerman, A. May 10–12, 1971. "Transport of Radionuclides in Sediments," *Proceedings of the Third National Symposium on Radioecology,* CONF-710501-p2, vol. 2, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Lerman, A., and G. J. Brunskill. November 1971. "Migration of Major Constituents from Lake Sediments into Lake Water and Its Bearing on Lake Composition," *Limnol. Oceanogr.* **16**(6): 880–90.

Lerman, A., and H. Taniguchi. May 10–12, 1971. "Strontium-90 and Cesium-137 in Water and Deep Sediments of the Great Lakes," *Proceedings of the Third National Symposium on Radioecology,* CONF-710501-pl, vol. 1, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Lerman, A. June 1972. "Strontium-90 in the Great Lakes: Concentration-Time Model," *J. Geophys. Res.* **77**(18): 3256–64.

Lin, W. L., I. H. Erhan, and A. H. Eraslan. 1978. *PREPAR: Automated Discrete-Element-Generator Program for Multiconnected Flow Regions with Geometrically Complex Shoreline Boundaries,* Environmental Impact Project Report, University of Tennessee, Knoxville.

Local Climatological Data, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, National Climatic Center, Asheville, N. C.

Miller, W. A., Jr. 1971. *Numerical Solution of the Equations for Unsteady Open-Channel Flow,* Georgia Institute of Technology, School of Engineering, Atlanta.

Murthy, C. R., G. Kullenberg, H. Westerbery, and K. C. Miner. 1974. *Large-Scale Diffusion Studies,* IFYGL Project 89 wm, Paper 14, Canada Centre for Inland Waters, Burlington, Ontario.

Near-Field Effects of Once-Through Cooling System Operation on Hudson River Biota, River Physics and Chemistry. 1977. Report prepared by Hudson Gas and Electric Corporation, New York.

Nishiwake, Y., et al. 1973. "Behavior and Distribution of Radioactive Substances in Coastal and Estuarine Waters," *Proceedings of the Symposium on Radioactive Contamination of the Marine Environment,* IAEA, Vienna (Seattle, Wash., July 1972).

O'Brian, G. G., M. A. Hyman, and S. Kaplan. 1950. "A Study of the Numerical Solution of Partial Differential Equations," *J. Math. Phys.* **29**: 223–51.

Officer, C. B. 1976. *Physical Oceanography of Estuaries (and Associated Coastal Waters),* Wiley, New York.

Onishi, Y. July 1977. *Finite Element Models for Sediment and Contaminant Transport in Surface Waters—Transport of Sediments and Radionuclides in the Clinch River,* BNWL-2227, Battelle Pacific Northwest Laboratories, Richland, Wash.

Paulson, R. W. 1970. "Variation of the Longitudinal Dispersion Coefficient in the Delaware River Estuary as a Function of Fresh Water Inflow," *Water Resour. Res.* **6**(2): 516–26.

Pence, G. D., J. M. Jeglic, and R. V. Thoman. 1968. "Time Varying Dissolved Oxygen Model," *J. Sanit. Eng. Div., Am. Soc. Civ. Eng.* **84**(SA2): 381–402.

Peterson, D. E., and R. T. Jaske. December 1970. *Potential Thermal Effects of an Expanding Power Industry: Ohio River Basin I,* USAEC Report BNWL-1299, Battelle Pacific Northwest Laboratories, Richland, Wash.

Pickens, J. F., W. F. Merritt, and J. A. Cherry. June 3, 1977. "Studies of Dispersion in a Sandy Aquifer," Paper H-62, presented at the National Spring Meeting of the American Geophysical Union, Washington, D. C.

Pritchard, D. W. 1971. "Hydrodynamic Models," Chap. 2 in *Estuarine Modeling: An Assessment,* ed. G. H. Ward, Jr., and W. H. Espey, Jr., Water Control Research Series 16070DZV 02/71, Tracor, Austin, Tex.

Pritchard, D. W. 1971. "Two-Dimensional Models," *Estuarine Modeling: An Assessment,* ed. G. H. Ward, Jr., and W. H. Espey, Jr., Water Control Research Series 16070DZV, Tracor, Austin, Tex.

Rifai, M. N. E., W. J. Kaufman, and D. K. Todd. 1956. *Dispersion Phenomena in Laminar Flow Through Porous Media,* Report 93-2, Institute for Engineering Research, University of California-Berkeley.

Roache, P. J. 1972. *Computational Fluid Dynamics,* Hermosa Publishers, Albuquerque, N. Mex.

Robertson, J. B., R. Schoen, and J. T. Barraclough. February 1974. *The Influence of Liquid Waste Disposal on the Geochemistry of Water at the National Reactor Testing Station,* Open File Report IDO-22053, U.S. Geological Survey, Water Resources Division, Idaho Falls, Idaho.

Robertson, J. B. May 1974. "Digital Modeling of Radioactive and Chemical Waste Transport in the Snake River Plain Aquifer at the National Reactor Testing Station, Idaho," U.S. Geological Survey, Water Resources Division, Idaho Falls, Idaho.

Ryan, P. J., and D. R. F. Harleman. 1973. *An Analytical and Experimental Study of Transient Cooling Pond Behavior,* R. M. Parsons Laboratory for Water Resources and Hydrodynamics, Department of Civil Engineering, Massachusetts Institute of Technology Technical Report No. 161, Cambridge.

Schlichting, H. 1960. *Boundary Layer Theory,* tr. J. Kestin, 4th ed., McGraw, New York.

Schubel, J. R. November 1969. *Distribution and Transportation of Suspended Sediment in Upper Chesapeake Bay,* Technical Report 60, Chesapeake Bay Institute, Johns Hopkins University, Baltimore.

Schureman, P. 1958. *Manual of Harmonic Analysis and Predictions of Tides,* Special Publication No. 98, U.S. Coastal and Geodetic Survey, U.S. Government Printing Office.

Seymour, A. H., and W. R. Schell. May 1977. *Distribution Coefficients for Transuranic Elements in Aquatic Environments,* Annual Program Report from the University of Washington to the U.S. Nuclear Regulatory Commission.

Shames, I. 1962. *Mechanics of Fluids,* McGraw, New York.

Shankar, N. J., and F. D. Masch. 1970. *Influence of Tidal Inlets on Salinity and Related Phenomena in Estuaries,* Technical Report HYD-16-7001, Hydraulic Engineering Laboratory, Department of Civil Engineering, University of Texas, Austin.

Soldat, J. K. July 1976. "Aquatic Exposure Pathways—Potential Exposure of Man from Environmental Transport of Waste Radionuclides," *Proceedings of the International Symposium on Management of Wastes from the LWR Fuel Cycle,* ERDA Report CONF-76-0701, Denver.

Sonnichsen, J. C., et al. 1972. *The COLHEAT River Simulation Model,* HEDL-TME 72-103, Hanford Engineering Development Laboratory, Hanford, Wash.

Stigter, C., and J. Siemons. 1967. *Calculation of Longitudinal Salt-Distribution in Estuaries as Function of Time,* Publication No. 52, Delft Hydraulics Laboratory, Delft, The Netherlands.

Struxness, E. G., et al. April 1967. *Comprehensive Report of the Clinch River Study,* ORNL-4035, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Tennessee Valley Authority. 1969. *The Computation of Daily Mean Stream Temperatures,* Water Resources Research Advance Report No. 11, Division of Water Control Planning, Engineering Laboratory, Knoxville, Tenn.

Thatcher, M. L., and D. R. F. Harleman. 1972. *A Mathematical Model for the Prediction of Unsteady Salinity Intrusion in Estuaries,* R. M. Parsons Laboratory for Water Resources and Hydrodynamics, Department of Civil Engineering, Massachusetts Institute of Technology Report No. 144, Boston.

The 1979 World Almanac. 1979. Newspaper Enterprise Association, New York.

Thom, A., and C. J. Apelt. 1961. *Field Computations in Engineering and Physics,* D. Van Nostrand, New York.

Thoman, D. C., and A. A. Szewczyk. 1969. "Time-Dependent Viscous Flow Over a Circular Cylinder," pp. 76–87 in *Phys. Fluids* (Suppl. II).

Tokar, J. V. August 1971. *Thermal Plumes in Lakes: Compilations of Field Experience,* ANL/ES-3, Argonne National Laboratory, Argonne, Ill.

U.S. Geological Survey, *Surface Water Supply of the United States—Part 3. Ohio River Basin,* Geological Survey Water Supply Papers 1810, U.S. Government Printing Office.

U.S. Geological Survey, *Surface Water Supply of the United States—Part 7. Lower Mississippi River Basin,* Geological Survey Water Supply Papers 1920, U.S. Government Printing Office.

U.S. Geological Survey. 1977. Private communications from Knoxville, Tennessee; Tuscaloosa, Alabama; and Nashville, Tennessee, district offices.

U.S. Nuclear Regulatory Commission. October 1975. *Reactor Safety Study—An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants,* Appendix VII—Release of Radioactivity in Reactor Accidents, Sect. 3.3.4, Report WASH-1400 (NUREG-75/014).

U.S. Nuclear Regulatory Commission. 1975. *Preliminary Safety Analysis Report, Clinch River Breeder Reactor Plant,* USNRC Docket Number 50-537.

U.S. Nuclear Regulatory Commission. September 1976. *Draft Liquid Pathway Generic Study,* NUREG-0140.

U.S. Nuclear Regulatory Commission. 1977. *Methods for Estimating Aquatic Dispersion of Liquid Effluents from Routine Reactor Releases for the Purpose of Implementing Appendix I,* Regulatory Guide 1.113, Rev. 1.

U.S. Nuclear Regulatory Commission. February 1978. *Liquid Pathway Generic Study,* NUREG-0440.

U.S. Nuclear Regulatory Commission. April 1981. *Final Environmental Statement Related to the Operation of San Onofre Nuclear Generating Station, Units 2 and 3,* NUREG-0490.

Ward, G. H., Jr., and W. H. Espey, Jr. 1971. "Case Studies" in *Estuarine Modeling: An Assessment,* ed. G. H. Ward, Jr., and W. H. Espey, Jr., Water Control Research Series 16070DZV, Tracor, Austin, Tex.

Ward, P. R. B., and H. B. Fischer. 1971. "Some Limitations on Use of the One-Dimensional Dispersion Equation, with Comments on Two Papers by R. W. Paulson," *Water Resour. Res.* 7(1): 215–22.

Water Resources Engineers, Inc., 1969. *Mathematical Models for the Prediction of Thermal Energy Changes in Impoundments,* Project 16130 EXT, prepared for the Water Quality Office of the Environmental Protection Agency.

White, J. E., and K. F. Eckerman. November 1982. *User's Manual for LPGS: A Computer Program for Calculating Radiation Exposure Resulting from Accidental Radioactive Releases to the Hydrosphere,* ORNL/TDMC-2 (NUREG/CR-2974), Oak Ridge National Laboratory, Oak Ridge, Tenn.

Winkle, W. Van, and L. W. Barnthouse. July 1977. *A Selective Analysis of Power Plant Operation on the Hudson River with Emphasis on the Bowline Point Generating Station,* ORNL/TM-5877/V1, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Yotsukura, N., H. B. Fischer, and W. W. Sayre. 1970. *Measurement of Mixing Characteristics of the Missouri River Between Sioux City, Iowa, and Plattsmouth, Nebraska,* Water Supply Paper 1899-G, Water Resources Division, U.S. Geological Survey, Idaho Falls, Idaho.

Yotsukura, N., and W. W. Sayre. August 1976. "Transverse Mixing in Natural Channels," *Water Resour. Res.* **12**(4): 695–704.

Appendix A

FORTRAN PROGRAM LISTING OF RADONE COMPUTER CODE

NRC FORM 335
(2-84)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

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12 SUPPLEMENTARY NOTES

13 ABSTRACT *(200 words or less)*

RADONE is a computer code for predicting the transient, one-dimensional transport of radionuclides in receiving water bodies. The model formulation considers the one-dimensional (cross-sectionally averaged) conservation of mass and momentum equations and the two coupled, depth-averaged radionuclide transport equations for the water layer and the bottom sediment layer. The coupling conditions incorporate bottom deposition and resuspension effects. The computer code uses a discrete-element method that offers variable river cross-section spacing, accurate representation of cross-sectional geometry, and numerical accuracy. A sample application is provided for the problem of hypothetical accidental releases and actual routine releases of radionuclides to the Hudson River.

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Sediment Layer
Unified Transport Approach
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